TESTING OF SYNTROLEUM FUELS IN DIESEL POWER PLANTS SUITABLE FOR ALASKA

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THESIS

Presented to the Faculty
of the University of Alaska, Fairbanks
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

By

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May 2005

ABSTRACT

Sulfur free synthetic diesel fuels can be produced using Gas to Liquid (GTL) technology, and may prove useful as a substitute for conventional diesel fuels when oil reserves are depleted. These fuels also should produce lower emissions, as the sulfur content is near zero. However, this fuel has significantly different combustion properties than conventional diesel fuels, and may require injection timing adjustments to burn cleanly.

This paper presents a comparison of the exhaust emissions from synthetic diesel fuels, manufactured by the Syntroleum Corporation, and conventional diesel fuel. Documented emissions are the total hydrocarbons, carbon monoxide and oxides of nitrogen. Effects of injection timing on exhaust emission and brake specific fuel consumption (BSFC) are also discussed.

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LIST OF ACRONYMS

Acronym	Expansion
PM	Particulate Matter
NOx	Oxide of Nitrogen
EPA	Environmental Protection Agency
CARB	California Air Resources Board
GTL	Gas to Liquids
F-T	Fischer Tropsch
DDEC	Detroit Diesel Engine Corporation
HDD	Heavy Duty Diesel
CFR	Code of Federal Regulations
TDC	Top Dead Center
NO	Nitrous Oxide
NO_2	Nitrogen Dioxide
CO	Carbon Monoxide
CO_2	Carbon Dioxide
O_2	Oxygen
THC	Total Hydrocarbons
FID	Flame Ionization Detector
DOE	Department of Energy
NREL	National Renewable Energy Laboratory
ASTM	American Society for Testing and Materials
SWRI	South West Research Institute
EGR	Exhaust Gas Recirculation
SSPD	Sasol Slurry Phase Distillate
FTP	Federal Test Procedure
HFET	Highway Fuel Economy Test

UL	Underwriters Laboratory
DAQ	Data Acquisition System
NDIR	Non Dispersive Infra Red

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank my advisor Dr. Dennis Witmer, who has always been a source of constant guidance, support and advice. I also would like to thank my co-advisor Dr. Chuen-Sen Lin, for his support and guidance and Dr. Ron Johnson for being a part of my thesis committee.

The funding for the project was provided by the Department of Energy, while project management was provided by I.C.R.C., and I greatly appreciate their support. A special mention must be made of the engineering staff at the UAF Energy Center, Mr. Jack Schmidt, Mr. Tristan Kenny and Mr. Tom Johnson, for their valuable help and support during experimentation. I would also like to thank my mother Mrs. Medha Telang and my brother Dr. Adwait Telang who have been a constant source of inspiration and guidance in my life. Finally, I would like to thank all my friends, especially my roommate Mr. Neil D'Cunha for all his help and assistance, and everyone who has made my stay in Fairbanks a memorable experience.

1.0 INTRODUCTION

Improving air quality from internal combustion engines has been a major environmental goal in the United States (US) since the 1970's, when the switch from leaded to unleaded gasoline allowed the use of catalytic converters to dramatically reduce pollutant levels from auto exhausts. The past decade has seen the government concentrate on drastically reducing diesel emissions as the next step to ensure cleaner air. The two major constituents of diesel emissions, particulate matter (PM) and the oxides of nitrogen (NOx) pose a dual threat to human health. NOx emissions significantly contribute to the formation of ozone at surface levels while PM is an identified human carcinogen. During 1990, the State of California identified diesel exhaust as a carcinogenic agent and listed it as a toxic air contaminant. In the year 2000, the Environmental Protection Agency (EPA) followed suit and labeled diesel exhaust as a probable carcinogen [1].

Local and federal governments have employed measures to contain and then reduce emissions from diesel engines. In 1998, the California Air Resources Board (CARB) adopted new standards to reduce emissions from diesel vehicles. All vehicles would have had to comply by the year 2004. A new revised set of standards were put in place for all model year 2004 diesel vehicles, which is very significant as it formed the basis of all the decisions made thereon by the US EPA.

On a federal level, the EPA, in the year 2000, agreed on a diesel emissions reduction plan to be imposed in two phases. The first phase came into effect in the year 2004 and concerns all heavy duty diesel engines manufactured in and after 2004. The 2004 final rule endorsed the fact that all adopted 2004 Non-Methane Hydrocarbons (NMHC) + Oxides of Nitrogen (NOx) emissions limits were feasible and a change in the diesel fuel properties would not be required to meet the standards. Phase 2 of the emissions reduction plan comes into effect in the year 2007. The 2007 rule calls for more stringent control over NOx emissions and defines new particulate standards. It also adopts the

introduction of low sulfur fuel, thereby reducing the diesel fuel sulfur level from 500 ppm to 15 ppm by July 1, 2006.

The following table lists the heavy duty exhaust emissions standards for the year 2007[2].

Table 1.1: Heavy Duty Emissions Standards for 2007

Emissions	Standards (g/bhp-hr)
NOx	0.20
NMHC	0.14
PM	0.01

Particulate Matter (PM) standards have to be met by engine manufacturers on all the engines that are sold. However, NOx and NMHC standards have to be met by only 50 % of the engines sold by a manufacturer in the years 2007, 2008, 2009, with a 100 % requirement in 2010.

To achieve phase II emissions standards, engine manufacturers and research agencies have employed two basic methods. The first approach employs exhaust after-treatment devices, which treat the exhaust gas prior to emitting it into the atmosphere [2]. This is achieved through a catalytic reduction/oxidation unit or a catalytic converter. Although a catalytic converter is an effective device for reducing emissions, it requires significant maintenance, as it is highly prone to deteriorate due the sulfur in conventional diesel, thereby increasing engine operation and maintenance costs. The second approach considers the modification of the combustion fuel. Research has centered on cleaner burning, low sulfur fuels, which will assist new or old diesel engines to comply with the new emissions regulations, with minimal or no cost for engine modification.

Recent increases in crude oil prices and depleting oil reserves have renewed public attention towards the need for an alternative energy sources, especially for transportation applications. The energy industry has explored the feasibility of converting natural gas to a hydrocarbon based liquid fuel oil generally called synthetic diesel through a process commonly known as a Gas to Liquid (GTL) conversion or a Fischer Tropsch (F-T) process [3] .The liquid product, a paraffin base fuel, has many of the properties of conventional diesel, the major difference being the lack of sulfur and the predominance of straight chain hydrocarbons. With each company producing its own blend and different companies competing for a strong foothold in an emerging global market for cleaner burning fuels, testing of newly developed fuel forms a critical aspect of producing and marketing a finished product.

Alaska has a unique issue with diesel engines and related emissions since electrical power generation in rural Alaska is predominantly through local diesel based power generation facilities. A large percent of these diesel engines are older models and operate primarily on conventional diesel. It is essential to conduct tests to determine the effects of the flexibility of the synthetic fuels in old and new diesel engines. It is highly desirable that any synthetic fuel oil is compatible with older model diesel generators and will still help the engine conform to the new emissions codes, without incurring heavy costs for engine modification.

The research conducted focuses on the testing of two such synthetic diesels. Both fuels were manufactured by Syntroleum Corporation, a company based in Tulsa, Oklahoma, and are marketed under the S-1 and S-2 brand names. Both fuels were delivered to the University of Alaska, Fairbanks, to be tested in a stationary diesel generator, similar to the ones used in Alaskan villages, and hence form a part of the verification process for this fuel.

Selection of the engine to be used for testing was the first major experimental decision. After careful consideration of possible generators for testing, a 2003 Detroit Diesel (DDEC) series 50, Heavy Duty Diesel (HDD) engine coupled to a 125 KW 208V generator was selected. There were two reasons for selecting this particular diesel engine. First, the Series 50 diesel engine is the only one in its class with electronic fuel injection control, thereby allowing us to change the injection timing. Second, the known sensitivity of the engine to injector failures is a possible failure mechanism attributed to the low lubricity of the synthetic fuel. This generator was installed in an instrumented test bed designed to measure engine performance, including engine emissions, thermal efficiencies and engine vibrations. However, this work will focus only on the comparative regulated emissions performance of synthetic and conventional diesel.

The major test objective was to operate the diesel generator for an extended time period of 2000 hours (selected time period was based on the availability of the test fuels and the need to complete the project in a reasonable time frame) on synthetic diesel and document any detrimental effects the fuel might have on the engine. During a major portion of the 2000 hour test, the diesel generator was operated on a variable load profile, to mimic typical generator loading conditions in Alaskan villages. Generator load was applied by a resistive/reactive load bank. The load bank had a digital interface, allowing the user to input a customized load profile and power factor. During emissions testing, the generator was operated on the 5-mode test cycle, as documented in the Code of Federal Regulations (CFR) Chapter 40 Part 89, for stationary diesel engines.

For the purpose of emissions comparison, baseline emissions data were obtained on conventional (No.1) diesel. These data were then compared to results obtained during operation on S-2 and S-1 synthetic fuels. Tests were conducted at the factory set injection timing of 10 degrees before Top Dead Center (TDC), a 3 and 5 degree advance in injection and a 3 degree retard in injection timing.

Regulated exhaust emissions were measured using an automotive portable emissions analyzer. Gaseous emissions measured by the analyzer were: nitrous oxide (NO) and nitrogen dioxide (NO_2) collectively known as NOx, and carbon monoxide (CO) along with carbon dioxide (CO_2), and oxygen (O_2). The portable analyzer employed electro-chemical cells for emissions measurements. A portable gas conditioner and a heated filter, placed up-stream from the analyzer, ensured a dry, particulate free sample gas supply. Total un-burnt hydrocarbons (THC) were measured with a separate Flame Ionization Detector (FID) analyzer. Measurements made in parts per million are presented in grams per kilowatt hour. Analysis of PM was not conducted during the experimentation.

2.0 LITERATURE REVIEW

2.1 Synthetic Diesel Properties

Synthetic diesel is a paraffin based fuel oil, consisting predominately of straight chain hydrocarbons [4]. It is mostly manufactured using the F-T process, in which a hydrocarbon feedstock is converted to a syn-gas rich in carbon monoxide and hydrogen, which is then converted back to a hydrocarbon in a catalytic reactor, typically with relatively long paraffin chains. However, most refiners have their own proprietary method for producing a finished product. Although dubbed as synthetic diesel, it differs significantly from conventional diesel created by the distillation of crude oil. Differences range from the method of distillation or manufacturing to the composition of the fuel. Synthetic fuel is a clear liquid with a wax-like aroma associated with it, containing non-detectable amounts of sulfur and very low aromatics, and boasting a very high cetane number, which is usually greater than 70. In comparison conventional diesel has a high aromatics percent (maximum 30 % by volume), a higher percent of sulfur (typically 500 ppm) and comparatively very low cetane number (generally ranges from 40 to 50) [4].

Production of conventional diesel from crude oil requires the feedstock be heated to its bubbling or boiling point, and fed into an atmospheric distillation column based on the desired distillates. Distillate separation is based on the vaporization temperatures of each individual product [5]. Although the specified properties of conventional diesel are within given limits from any refinery, properties of the diesel fuel will depend on the distillation process and the composition of the crude oil. Additive packages and further refinement of the diesel fuel are generally employed, depending upon the desired quality of the final product.

For the production of synthetic diesel, a typical distillation column is not used. Three distinct steps may be identified for the production of F-T fuel [6]. The process is initiated by the production of Syn-gas, which may be produced from any carbonaceous material,

such as coal, natural gas or biomass. The second step utilizes an F-T catalyst that converts the syn-gas to hydrocarbons. The catalyst used by a company is mostly proprietary and the information is never divulged. Finally there is a post processing phase, from which the final finished product is achieved.

The S-2 synthetic diesel is produced, by Syntroleum, using a proprietary gas to liquids technology called the Syntroleum Process. The feed stock consists of natural gas. The process is initiated by introducing natural gas into an "auto-thermal reformer". The reformer produces a mixture of carbon monoxide and hydrogen (along with nitrogen from the atmosphere) which is called as Synthesis gas or Syn-gas. The syn-gas is introduced into a reactor with a catalyst. Since F-T catalysts are sensitive to any sulfur, it is ensured that the syn-gas is sulfur free. The gas undergoes a F-T chemical process and is converted to a long chain hydrocarbon known as Syn-Crude, with relatively high melting temperatures [7]. The syn-crude then undergoes a fuel finishing stage where the long chain hydrocarbons are broken into lengths comparable to those of conventional diesel fuel. The entire process imparts a unique set of properties to the final product, such as zero sulfur levels, a very high cetane number and the absence of poly-aromatics, olefins, metals and alcohols [4]. The following table compares a few properties of Conventional and S-2 Synthetic Diesel

Table 2.1: Properties of Synthetic and Conventional Diesel [4]

Fuel Property	Conventional Diesel	S-2
Sulfur (ppm)	350	0
Aromatics (ppm)	31	0
Cetane Number	47	74
Heating Value (Btu/gal)	130,000	120,000
Specific Gravity	0.85	0.77

2.2 Emissions Based on Fuel Composition

In order to understand the effect of the components of diesel fuel on the emissions produced, various agencies have conducted emissions tests on an array of fuels including conventional diesel, low sulfur diesel and various diesel blends to obtain a correlation matrix between fuel composition and the emissions produced. Low sulfur diesel fuel, in the absence of any sulfur, enables catalytic clean up and forms a vital aspect of emissions testing. The following is a discussion of the effects of the various fuel components on the exhaust emissions, thereby hopefully providing some insight about the emissions that may be produced by the S1 and S2 fuels. Please note that this issue is both controversial and complicated, and different authors have proposed various explanations for the observed results. The discussions below are not intended to endorse any particular model. Fuel parameters discussed are the fuel sulfur content, the aromatic content, distillation temperature, density and the cetane number.

2.2.1 Sulfur

Sulfur is a naturally occurring element in crude oil. Typical current transport diesel fuels contain a maximum of 500 ppm sulfur. During in-cylinder combustion, fuel sulfur is oxidized to sulfur dioxide (SO_2) or sulfur tri-oxide (SO_3). With moisture available in diesel exhaust, SO_2 or SO_3 forms sulfuric (H_2SO_4) or sulfurous (H_2SO_3) acid aerosols [8] and sulfur particulate matter. Diesel exhaust stacks are generally made from mild steel and either acid may, over a time period assisted by the exhaust condensate, will initiate and accelerate metal corrosion.

Research has suggested that a major fraction of fuel sulfur is converted to SO_2 (typically 98% sulfur) and only a small fraction to SO_3 and sulfates (approximately 2 % of fuel sulfur) [9]. The quantity of SO_2 produced is governed only by the quantity of sulfur available during combustion, which comes from the fuel sulfur and sulfur in the engine

oil [10]. However, the contribution from the fuel is much greater, since the design of the engine is intended to prevent significant quantities of lubricating oil from being consumed during normal operations. It should be noted that there still will be some residual sulfur in the emissions from the combustion of the engine oil even if the fuel is entirely sulfur free.

The 2006 EPA regulations will require a mandatory reduction in sulfur in transportation diesel fuel, from 500 ppm to 15 ppm [11] [12]. Emissions standards applied to on-road diesel engines will also extend to off-road engines, including diesel generators, which have to comply by the year 2011 [1]. Synthetic diesels manufactured by the F-T process have sulfur levels as low as 0.001% to 0.002% (10 to 20 ppm) and are considered to be sulfur free fuels and hence would assist in meeting the EPA diesel sulfur requirements for 2006. However refiners have also developed processes to remove the majority of sulfur from distillate fuels at costs considerably under the cost of producing synthetic diesel fuels, so the imposition of low sulfur standards is not expected to be a single major driver. The detrimental effects of sulfur on after-treatment devices have been documented in a study conducted by the Department of Energy (DOE), National Renewable Energy Laboratory (NREL), Engine Manufacturers Association, Manufacturers of Emission Controls Association, Caterpillar Inc. and Oak Ridge National Laboratory [2]. The study evaluates four exhaust after-treatment devices, namely, the Diesel Oxidation Catalysts, Lean NO_x Catalysts, Diesel Particulate Filters and NO_x Adsorber Catalysts, which help reduce regulated emissions from diesel engines. All four technologies were found to be affected by the presence of any amount of sulfur in the diesel fuel. The useful life of the device was found to be directly proportional to the quantity of sulfur present. Zero or non-detectable quantities of sulfur, as in synthetic diesel fuels, would help accommodate exhaust after-treatment devices and assist in reducing all regulated emissions.

However, not all the effects of sulfur in diesel fuel are negative as it imparts the much needed lubricity to the fuel oil [12]. Engine components, such as fuel injectors rely on the lubricating aspect of the fuel to minimize wear during operation. With zero sulfur, synthetic diesels generally have a problem meeting the American Society for Testing and Materials (ASTM) minimum fuel lubricity standards. In such circumstances, an additive package is required to provide the fuel lubricity [13].

2.2.2 Aromatics

Aromatics are defined as a form of hydrocarbons based on the benzoid ring and having three double bonds. The general chemical formula for aromatics is C_nH_{2n-6}, with benzene being the simplest form. Compounds with more than one aromatic ring are called polycyclic aromatic hydrocarbons (PAH) or polynuclear aromatics (PNA); hence diesel aromatics may be differentiated into mono and poly aromatics depending on their molecular structure. The EPA currently regulates the quantity of aromatics in highway diesel to no more than 35 % volumetric [14]. On an average, conventional diesel fuel contains 30 % aromatics by mass. On a fractional basis diesel contains approximately 70% mono-cyclic, 27 % bi-cyclic and the remaining 3 % may be grouped into polycyclic aromatics. When compared to conventional diesel, synthetic diesel is said to contain very low or non detectable levels of aromatics [4]. Aromatic compounds are, in general, more toxic than paraffins, and contribute strongly to the negative environmental effects of spilled diesel fuels.

Diesel emissions models developed by various testing agencies indicate a strong correlation between the fuel oil aromatic levels and the quantity of NOx and PM produced during combustion [15] [16] [17] [18]. Although the correlation has been established, models developed by various agencies have not been consistent, which may be attributed to the different testing conditions.

For example, a model developed by the South West Research Institute (SWRI) for Shell Oil correlates the total aromatics in a fuel oil to the NOx emissions [17]. Testing conducted by Shell and Mercedes Benz report zero correlation between the aromatics and the NOx produced, but concludes that the cetane number plays a vital role in determining NOx levels in emissions [16].

One reason why emissions results are inconsistent may be because emissions results are highly dependent upon the engine and the fuel used during experimentation. This is likely due to the fact that emissions depend not only on the composition of the fuel, but also on the dispersion of the fuel within the cylinder during combustion, and therefore on the details of injection, which are unique and vary from design to design and engine to engine.

Prior to the beginning of testing, the literature review suggests that with no aromatics, NOx emissions from the synthetic fuel should be lower, if not very low, as compared to conventional diesel. It should be noted that there are other governing factors, such as the temperature of combustion, that have been seen to have a definite effect on the quantity of NOx produced.

The dependence of the production of PM on fuel aromatic levels may be understood on a similar basis. Most reports have shown a decrease in PM levels with a decrease in the fuel aromatics [16] [19]. The decrease in PM formation is also attributed to the percent (by mass) of bi and poly-aromatics but shows no correlation with the quantity of mono-aromatics in the fuel [16]. The conclusions reached so far have been based on standard testing of conventional diesel, low sulfur diesel, CARB diesel and their various blends. Tests were conducted on various diesel engines and results were published based solely on the effect of the test fuel on the emissions. It should be noted that production of PM also depends upon in-cylinder mixing characteristics of fuel and air, and therefore on the details of injection.

2.2.3 Distillation Temperature

The distillation temperature is the temperature at which a fraction or whole of the fuel oil will distill. It is generally denoted by T30, T60 or T90 representing 30%, 60% or 90% distillation. The temperature signifies the vaporizing capacity of the diesel fuel and hence plays a vital role during combustion.

During diesel emissions testing, the distillation temperature has also been considered as an independent variable and its effects on emissions documented. As understood, a lower distillation temperature should correspond to better combustion and thereby reduce emissions such as THC.

Tests conducted on conventional diesel, low sulfur diesel and various other blends have generally indicated no correlation between the T90 distillation temperature and the emissions produced. However, certain tests conducted have shown an increase in PM with increasing T50 and T90 distillation temperatures [20].

2.2.4 Fuel Density

The density and the heating value of the fuel play an essential part in determining fuel consumption. Conventional diesels generally have a oil density of 0.85 kg/liter at 15°C and 34 API gravity while synthetic diesels have a lower fuel density of approximately 0.77 kg/liter.

According to some emissions models the quantity of PM and NOx in diesel exhaust has a strong correlation with the density of the fuel oil [19]. Tests conducted indicate a positive correlation between fuel density and PM emissions for transient testing conditions, while such a correlation could not be established for steady state testing [20]. The dependence of NOx emissions on the density has a highly varied response. While some models report

an increase in NOx with an increase in density others failed to identify any correlation [20].

With varying results from different reports it becomes very difficult to infer an increase or decrease in the emissions with the density of the fuel oil. However, variation of fuel emissions with density may be understood on the basis of the physical characteristics of the fuel. A fuel with lower density will have a higher volumetric flow rate at a rated load, as compared to a fuel with higher density and hence a longer injection period will be required to meet the engine needs. With higher engine speeds, this may result in incomplete combustion in the cylinder, and a rise in HC, CO and PM emissions, with a decrease in the NOx emissions [20].

2.2.5 Cetane Number

The cetane number defines the ignition quality of a fuel oil [8]. A low cetane number corresponds to poor ignition while a high cetane number generally means better ignition properties. For diesel fuels the cetane number varies from a minimum of zero to a maximum of 100. ASTM specifies a minimum cetane number of 40 for all conventional diesel fuels. When compared to conventional diesel, synthetic diesel fuels tend to have a higher cetane number, usually in the range of 70 to 80.

Emissions models developed by testing agencies show that a higher cetane number translates into lower NO_x production, with other fuel parameters remaining constant [16] [17], although the effect is also dependent upon the level of engine technology. The correlation is seen to weaken however, for cetane numbers exceeding 60 [21].

Some tests have also established correlations between the cetane number, HC and CO emissions. However, most tests that exhibit this correlation were conducted with 1991 or older engine technologies. With advancement in engine technology, it is seen that new

diesel engines, such as advanced diesel engines equipped with Exhaust Gas Recirculation (EGR) technology [20] [21] [22] exhibit a weak correlation between the cetane number and NOx emissions

2.3 Synthetic Diesel Emissions

Emissions tests on paraffin base diesel fuels have been conducted by very few agencies. With almost no sulfur, the fuel is expected to produce almost no oxides of sulfur. Based on the emissions models produced by various agencies, synthetic diesel should burn cleaner with lower emissions as compared to conventional diesel and CARB diesel. Available emissions data on synthetic diesel is very promising. Most tests analyze for regulated as well as non-regulated emissions. Results from major manufacturers for synthetic diesel, such as Sasol, in South Africa, and Shell, Malaysia, have shown a decrease in overall emissions levels. Synthetic diesel may be produced from various sources, such as coal or natural gas, by the F-T reaction. Although the quantity of aromatics and olefins, etc., and the production process may vary, all synthetic diesels have zero or non-detectable amounts of sulfur [6].

Tests performed by Sastech Research Development and the SWRI in 1997 on a synthetic diesel called Sasol Slurry Phase Distillate (SSPD), have produced encouraging results [23]. SSPD is similar to the S-2 fuel, with no sulfur, no aromatics and a very high cetane number. Testing was done on a 1991, heavy duty diesel engine. When compared to conventional diesel the SSPD showed a decrease in HC, CO, NO_x, and PM emissions by 49 %, 33 %, 27 % and 21 % respectively. When compared to CARB diesel the decreases in HC, CO, NO_x, and PM were 15 %, 23 %, 15 %, and 21 %, respectively.

A test, performed by Syntroleum Corporation and SWRI in 2001, compared emissions from an F-T fuel manufactured by Syntroleum, Swedish diesel, bio-diesel and CARB diesel [24]. Testing was performed on a 1999, 5.9 L direct injection Cummins "B-Series"

diesel engine. Emissions were measured with the HDD connected to a dynamometer using the EPA transient emissions test cycle. Emissions results for all four fuels were seen to be below the required limits, with the low sulfur Swedish diesel having the highest emissions. When compared to the Swedish diesel, the F-T fuel showed a reduction in THC by 41%, CO by 38%, NOx by 20% and particulates by 40 %.

In 2002, a second test was performed by Syntroleum Corporation and SWRI, on a 1.9 L Volkswagen Golf GL TDI operating on the S2 fuel [25]. Three emissions test cycles were used, the Federal Test Procedure (FTP) transient cycle, the Highway Fuel Economy Test (HFET) and the US06 aggressive driving cycle. When operated on the FTP cycle, all regulated emissions, including particulates, were seen to decrease. However NOx emissions were seen to increase. The HFET test showed similar results. While the particulates were seen to decrease by 70 %, the NOx emissions were seen to increase by approximately 4%. With the US06 emissions test, similar results were obtained, with a decrease of 90% in particulates and an increase of 1% in NOx emissions, when compared to conventional (No.2) diesel. However, higher NOx emissions from the Syntroleum S-2 fuel is compensated by the fact that the Syntroleum S-2 fuel is sulfur free and will not have any detrimental effects on any exhaust after-treatment device. The 2007 emissions regulation may be met by using NOx adsorber catalysts and particulate traps [26].

Although beneficial from an emissions viewpoint, zero sulfur fuels are anticipated to have a lower fuel lubricity as compared to conventional diesel. Manufacturers need to blend a lubricity additive in order to maintain fuel lubricity and prevent undue fuel system wear. During an experiment conducted by NREL, West Virginia University, and the DOE, F-T fuel manufactured by Shell, Malaysia was seen to fail the ASTM D6076 high frequency reciprocating rig (HFRR) lubricity [27] test. Prior to experimentation, a lubricity additive, Paradyne 655, was added to the F-T fuel. Tests were conducted on a Detroit diesel series 60, using a 5 mile test cycle. The fuel showed promising results with

a decrease in all the regulated emissions including NOx, as well as un-regulated emissions.

3.0 EXPERIMENTAL SET-UP

The following is a brief description of the test bed used for all experimentation. The test bed is installed outside the Energy Center, located in the Mineral Industry Research Laboratory building, at the University of Alaska Fairbanks. The test bed was installed in May 2003. Prior to commencing testing, modifications to the test bed were undertaken to help facilitate testing and installation of test equipment and sensors. All sensors were meant for monitoring the engine performance at all stages of experimentation, and were intended not to interfere in normal engine operation. The following is a brief description of the test bed and instruments used to monitor engine performance.

3.1 General Description

In order to simplify installation, and have the ability to be placed outdoors, the diesel generator and related equipment were installed in a 40 foot long x 10 foot wide insulated conex box. This is a regular conex box that is used to transport cargo. With the exception of ports cut for air-circulation and electrical feedthroughs, no major modifications were necessary to the conex to accommodate all the equipment. The conex was placed outside and hence exposed to ambient conditions. The conex houses the following equipment:

1. *One* Diesel generator.
2. *Two* day tanks.
3. *One* inlet air after-cooler.
4. *One* coolant radiator.

Along with the equipment placed inside the conex, an 8000 gallon bulk fuel storage tank and a resistive/reactive load bank were placed adjacent to the conex box.

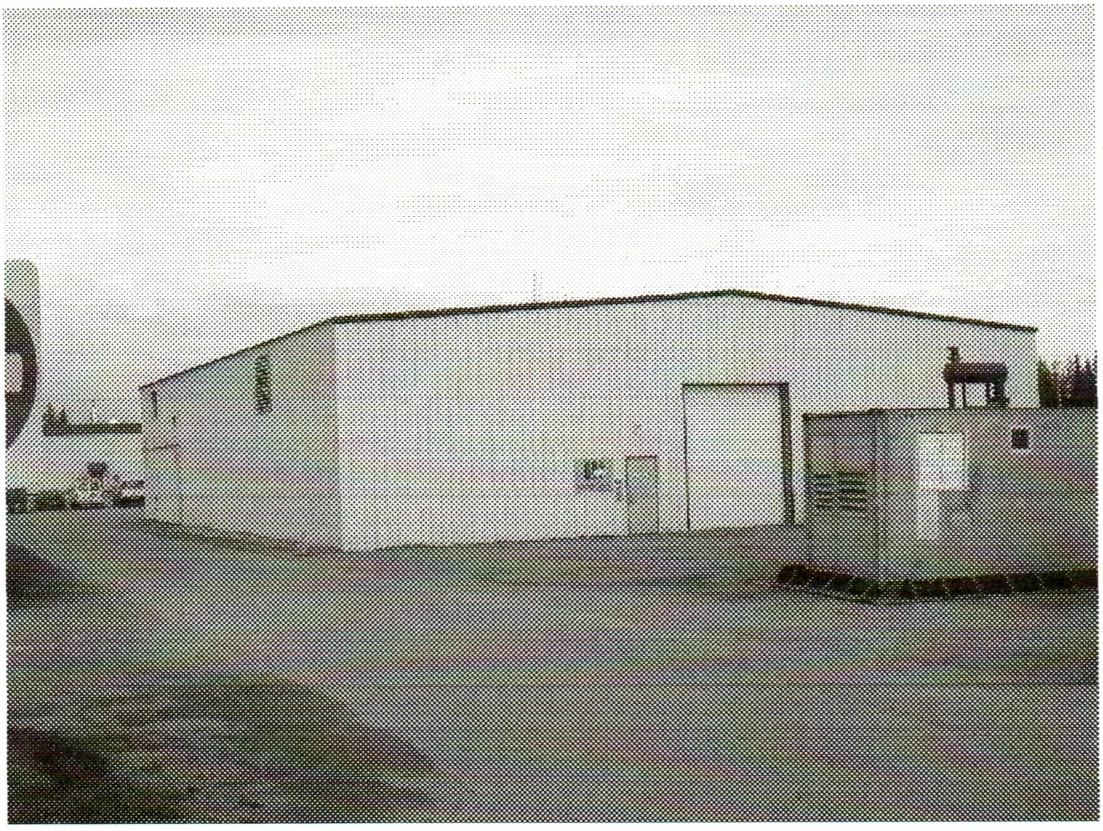

Figure 3.1: Energy Center, University of Alaska Fairbanks

3.2 Generator

The core of the test bed is a 4 cylinder Detroit Diesel Series 50 Heavy Duty diesel engine. The engine is rated at 235 KW and operates at a constant speed of 1200 rpm. The engine is not fitted with a reduction catalyst nor does it employ EGR. The engine is coupled to a 125 KW generator operating at 1200 rpm. The series 50 diesel engine is currently the only engine in its class to employ an electronic fuel injection control system, thereby providing the user the ability to modify the injection timing, with appropriate software from Detroit diesel. In view of the lubricity issues related to synthetic diesel fuel, the series 50 injectors highly depend upon the lubricity of the fuel, to reduce injector wear during operation. If the test fuel did have low lubricity it would be reflected in the shortening of injector life.

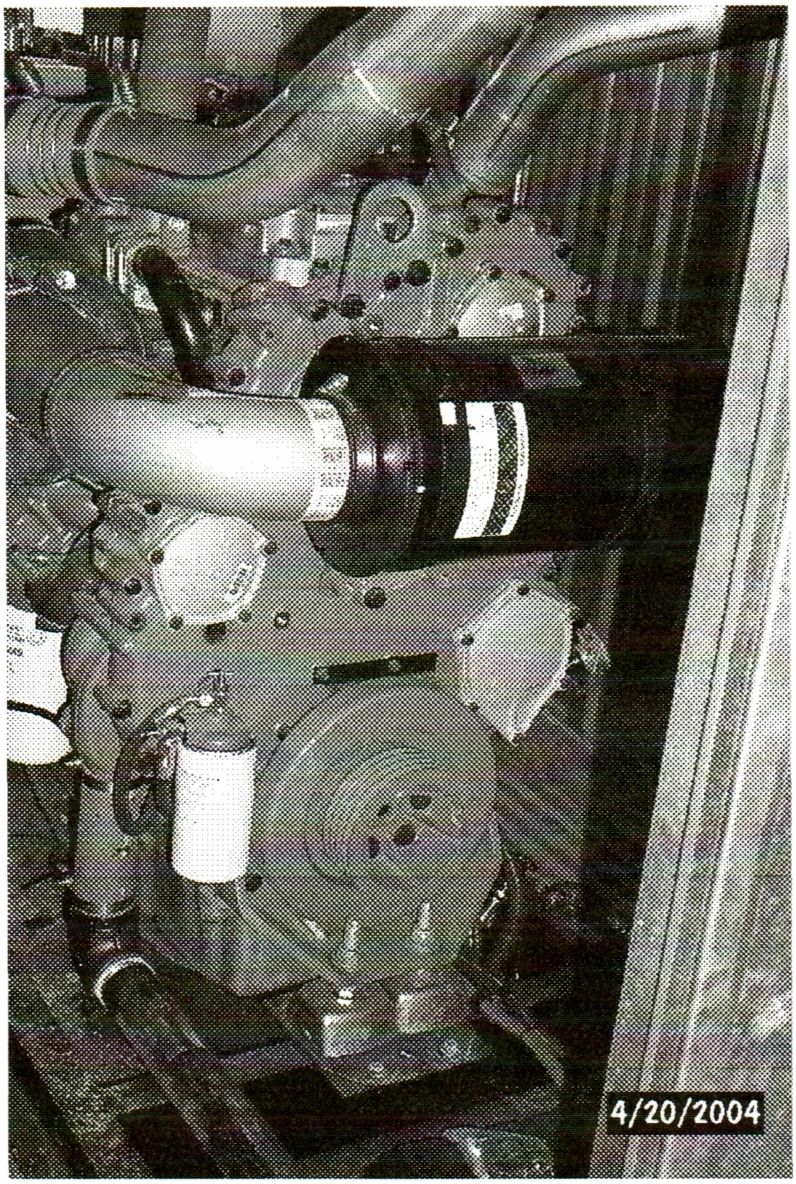

Figure 3.2: Detroit Diesel Series 50 Diesel Engine.

Most of the diesel generators in Alaska operate at 1800 rpm, regardless of the manufacturer. Shortly before procurement of the diesel generator from Detroit diesel, a major black-out in the continental USA drastically increased the demand for diesel generators. With a need to start experimentation to meet test deadlines, it was decided to procure a 1200 rpm generator, rather than wait for a few months for an 1800 rpm engine.

Although, the generator is rated at 1200 rpm, it does not differ in the wear characteristics or effects of operating conditions as compared to an 1800 rpm engine.

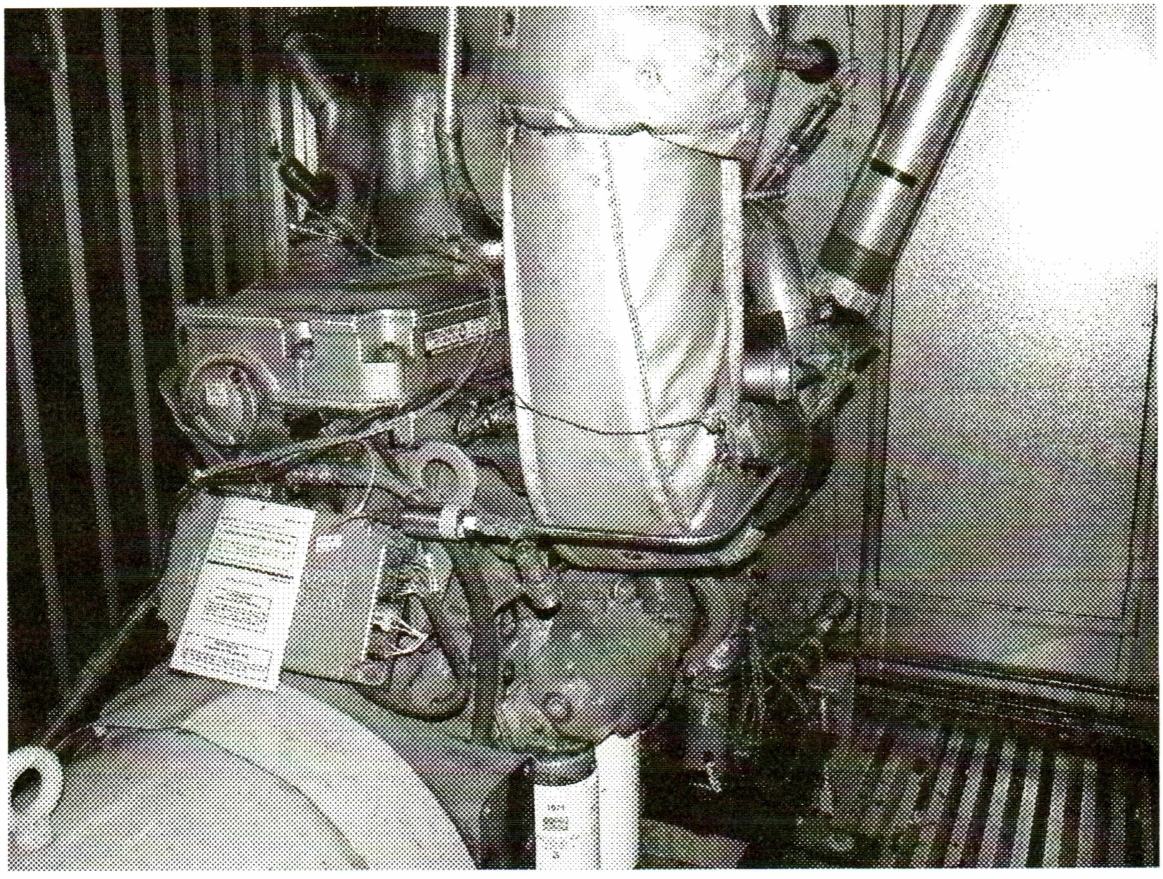

Figure 3.3: Detroit Diesel Series 50 Engine and Generator

The series 50 is coupled to a 3 phase AC generator rated at 125 KW and operating at 1200 rpm. In order to mimic a typical generator operating in an Alaskan village, load was supplied to the generator using a 125 KW resistive/reactive load bank manufactured by SIMPLX. The load bank employs a digital user interface, located inside the conex. The interface allows the user to input a customized load profile, in our case from a LabVIEW program, to the generator, and also set a desired power factor. The load bank is placed outdoors, adjacent to the generator, and is rated for all weather conditions.

In order to accurately calculate the total electrical load on the generator, all load bank accessories were connected to a separate 220 V harness supplied by the university. However, power for on-board electronics and fans for the load bank, also termed as

Figure 3.4: Load Bank

parasitic load, is supplied by the generator. The parasitic power forms the difference between the actual load and the input load, and can be calculated easily. Therefore a generator actual load of 125 KW is divided into a 115 KW input load and 10 KW parasitic load. The parasitic load is not constant and will vary with generator loading conditions.

3.3 Fuel Storage

3.3.1 Bulk Fuel Storage

In order to meet the stated program goal of 2000 hours of testing, it was estimated that a total of 15000 gallons of synthetic diesel would be required. The fuel was supplied by Syntroleum and shipped in three different batches, over the duration of testing. An 8000 gallon, bulk fuel storage tank was used for long term on site fuel storage. The tank is double walled and conforms to the Underwriters Laboratories (UL) standards. An inbuilt partition separates the tank into two separate reservoirs of 3000 and 5000 gallons.

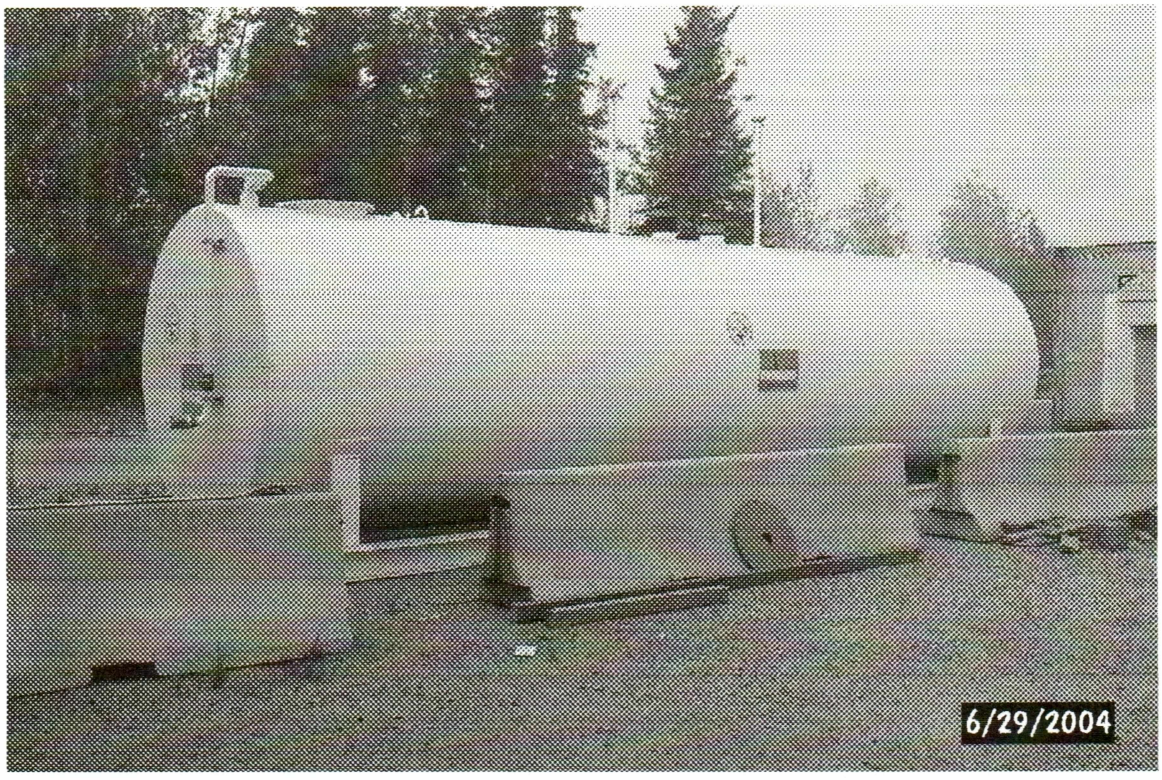

Figure 3.5: Bulk Fuel Storage Tank

The tank is located adjacent to the conex. An attached fuel pump and hose assembly allows easy transfer of fuel from the bulk tank to either of the two day tanks. The transfer

pump is also equipped with a metering system, which measures all fuel transfers from the bulk tank. Any fuel delivered into the tank is accounted with the help of a tank level indicator. The level indicator reading is easily converted to available fuel in gallons using a supplied table.

3.3.2 Day Tanks

Fuel storage for daily operation is accomplished with the help of two separate day tanks. Both day tanks are located inside the conex. The synthetic diesel and conventional diesel were stored in the two separate day tanks, to prevent cross contamination during testing.

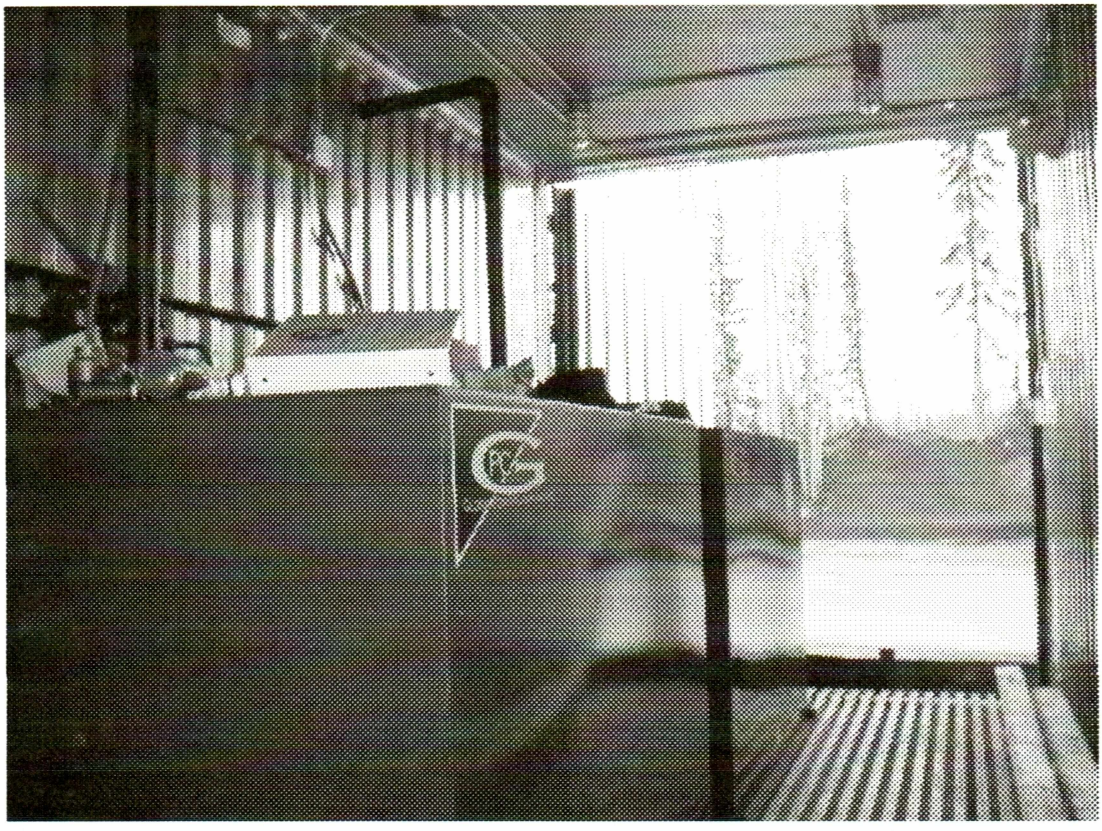

Figure 3.6: Day Tanks

Care was taken that no day tank was used for two fuels, without being completely drained; therefore there was no un-intended mixing of fuels during experimentation. Both the tanks are double walled with a 300 gallon capacity and have a UL certification. The tanks were plumbed such that fuel could be pulled from either tank during operation. Both tanks were equipped with independent low level and overflow alarms. Vents provided on top of the tanks ensure that the ambient conditions inside the conex are not contaminated by aromatics or light-ends that may tend to evaporate during engine operation.

3.4 Data Acquisition System (DAQ)

The DAQ forms the hub for data acquisition and storage. The DAQ comprised of the transducers for the various parameters of interest, excitation power supplies, and a cabinet mounted National Instruments PXI chassis with supporting modules.

Transducers requiring external excitation were provided excitation from an auxiliary 24 volt DC power supply or an internal 10 volt DC supply on a data acquisition module. Output from devices with a 4-20 milliamp current output was passed through a precision 249 ohm resistor to generate a 1 – 5 volt DC signal. Voltage and current signal wiring with the exception of thermocouple wiring was routed through an intermediate junction box in the data acquisition cabinet to facilitate troubleshooting and calibration. Thermocouple wiring was terminated at the thermocouple terminal block.

The data acquisition system was housed in a cabinet with the junction box and auxiliary power supply. The cabinet environment was moderated with a temperature controlled ventilation fan and vent supplying outdoor air. The temperature control was employed to prevent overheating of the data acquisition system caused by elevated temperatures in the generator enclosure.

The National Instruments data acquisition system was comprised of the following:

1. PXI Chassis

PXI 1042	Pentium based chassis
PXI 4472	Dynamic signal acquisition module for vibration
PXI 8464	CAN bus data acquisition
PXI 6070E	Input from auxiliary SCXI chassis

2. SCXI Chassis

SCXI 1120	Analog input 0-10V DC (4 modules)
SCXI 1121	Analog input 0-10V DC with excitation
SCXI 1102	Thermocouple amplifier

3.5 Emissions Sensors

Emissions testing were performed on both grades of synthetic diesels and on conventional diesel. Emissions were measured using an ECOM AC Plus portable emissions analyzer and a JUM FID analyzer. Both analyzers were rented from Clean Air Rentals, a very reputable supplier of well maintained and calibrated environmental testing equipment. The ECOM analyzer uses electro-chemical sensors to detect regulated gaseous emissions, namely CO, NO and NO_2 along with O_2 and CO_2. The un-burnt hydrocarbon emissions were measured using the FID analyzer.

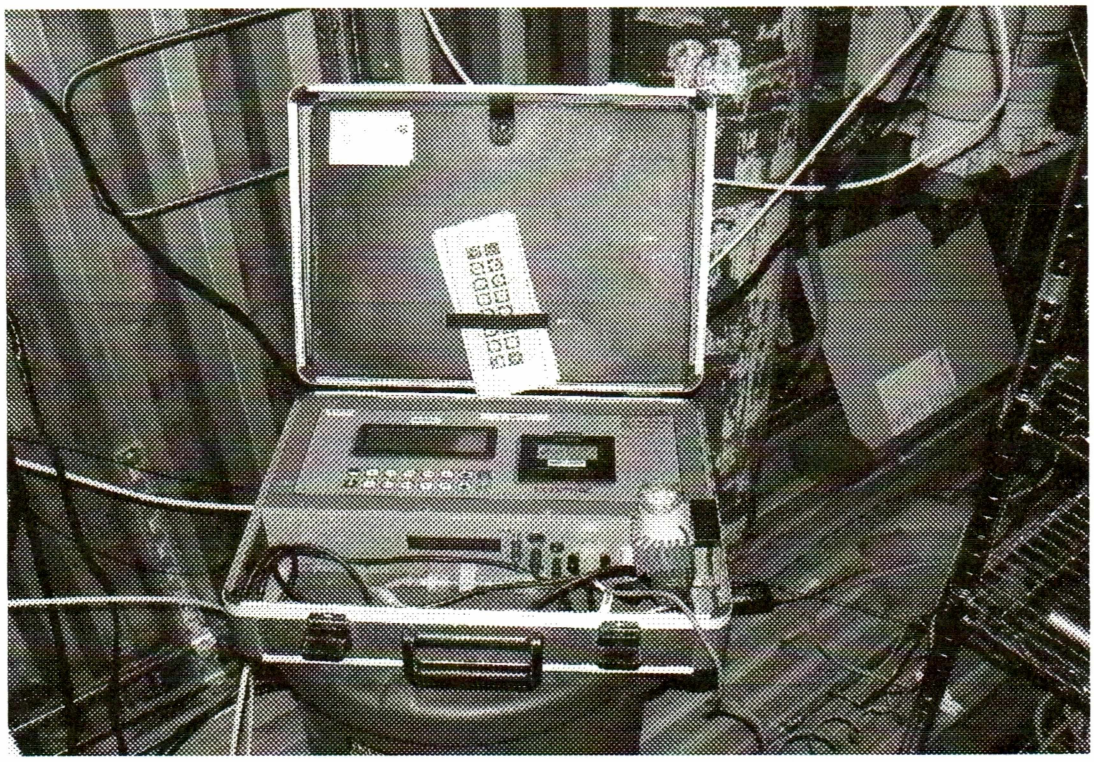

Figure 3.7: ECOM Portable Gas Emissions Analyzer

All the emissions test equipment was installed inside the conex. Sample exhaust gas was extracted with a heated sample probe inserted one foot below the exhaust stack exit. Care was taken with the probe placement and associated fitting so that there was no ambient air sucked into the sample exhaust stream during testing. The heated sample probe was attached to a heated filter, which ensured a particulate free sample exhaust supply to prevent damage to the emissions equipment. The heated filter, probe and the sample line were maintained at 250°F. This ensured against any condensate formation in the lines.

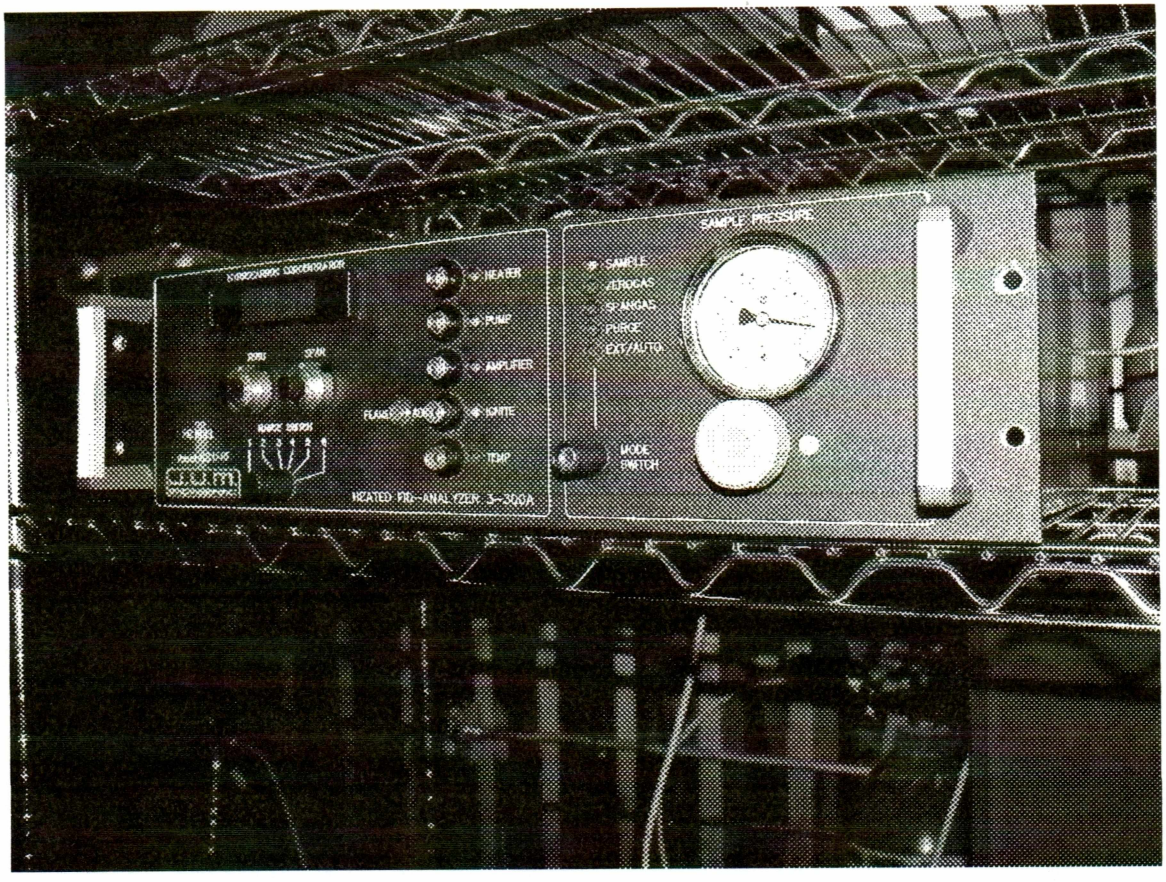

Figure 3.8: FID Exhaust Hydrocarbon Analyzer

In order to supply both analyzers, the sample flow was split. The equipment supplier stated that the FID analyzer is not affected by the available moisture in the exhaust. On the contrary, the ECOM analyzer, with electro-chemical sensors, is highly sensitive to any amount of water vapor in the sample exhaust. A portable gas conditioner/chiller, placed downstream from the ECOM analyzer, ensured a vapor free sample gas supply to the ECOM analyzer.

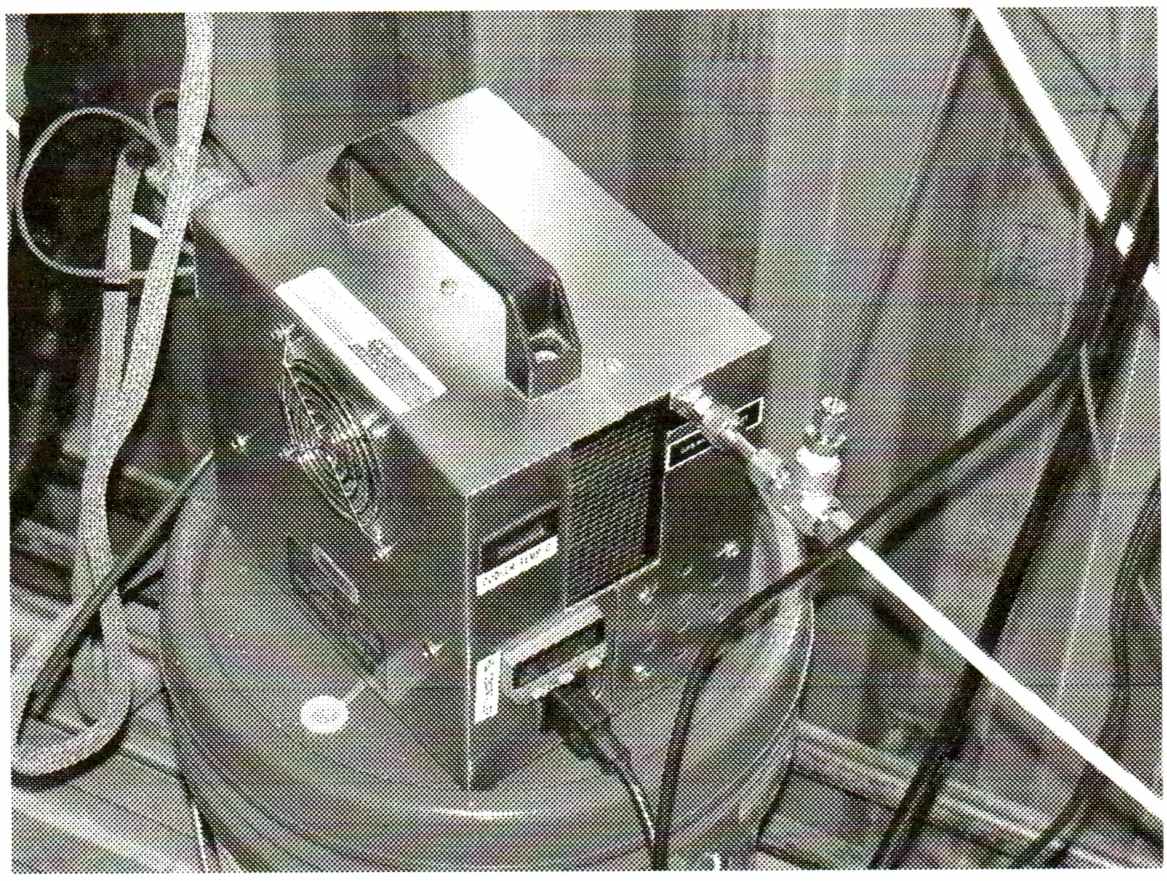

Figure 3.9: Portable Gas Conditioner

Emissions data from the ECOM were monitored and stored using data acquisition software provided by the manufacturer and installed on a dedicated computer. Emissions were monitored continuously during testing with an acquisition rate of 10 seconds. The FID analyzer had a 1 to 5 volt output and was connected to the main DAQ.

3.6 Air Flow Measurement

Accurately measuring the mass flow rate of air available for combustion forms a very important aspect during any form emissions testing. A small error in calculated air flow could translate into a major miscalculation in the emissions produced by the diesel engine.

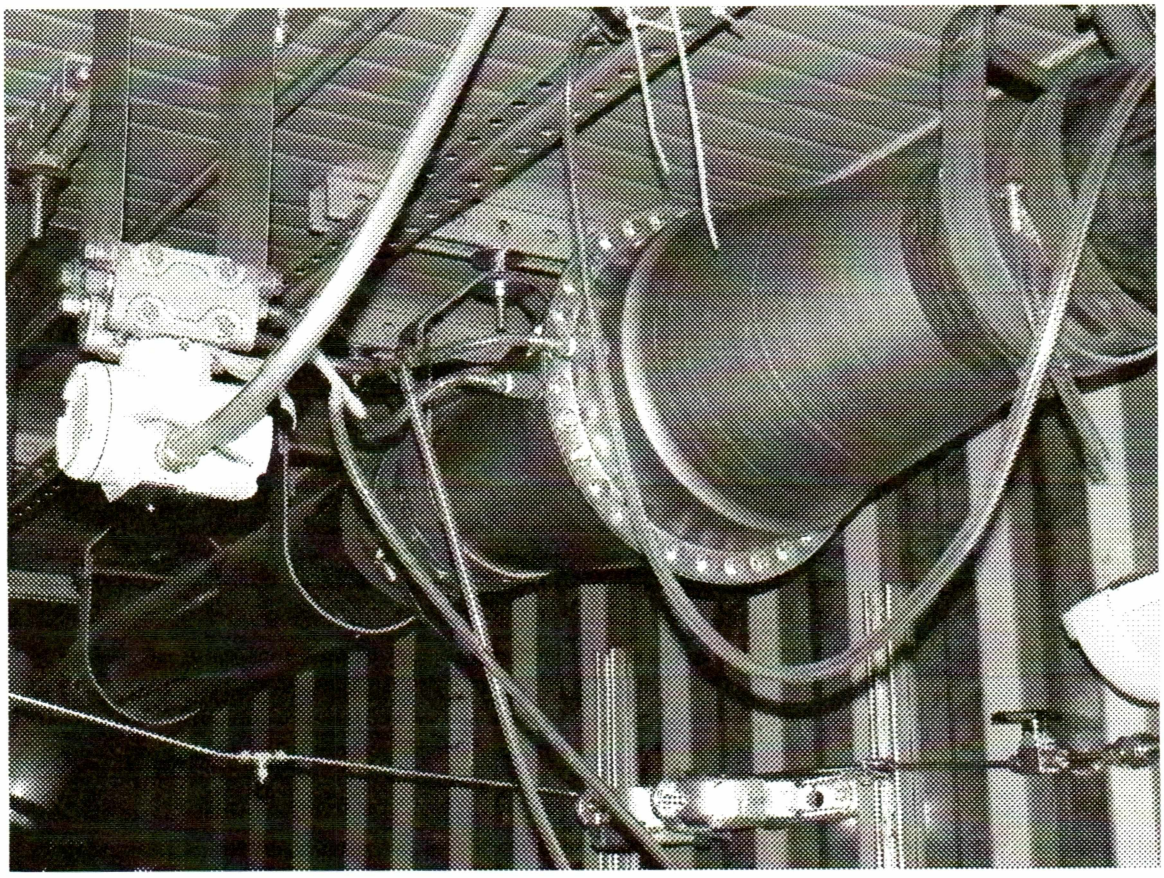

Figure 3.10: Laminar Flow Element & Differential Pressure Meter

Air flow data were measured using a laminar flow element (Model 50 MC2-6) manufactured by Mariam Instrument, coupled with a HART differential pressure transducer manufactured by ABB. The air inlet system, for the engine, was modified from its initial configuration to accommodate the laminar flow element. The laminar flow element was located on the air inlet line, after the inlet air filter.

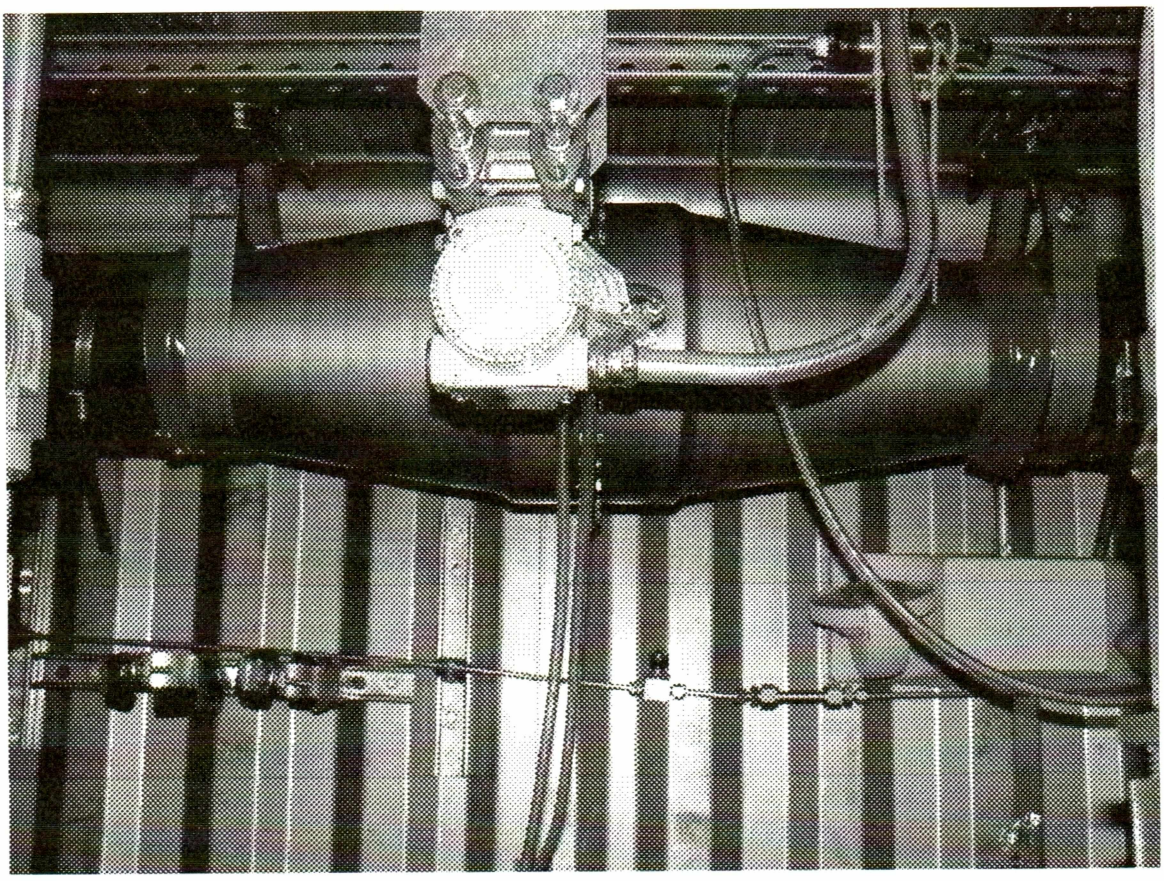

Figure 3.11: Laminar Flow Element and Differential Pressure Meter

The laminar flow element has a honey-comb internal structure. The pressure drop across the honey comb interior is proportional to the volumetric flow of air through the element. The HART differential pressure transmitter was connected across the ends of the laminar flow element and is exposed to the pressure drop across the element. The differential pressure meter was calibrated from 4 to 20 milliamps representing 0" to 4" WCG pressure drop across the element.

The recorded differential pressure was then converted to a volumetric flow rate of standard cubic feet per minute and eventually to a mass flow rate. Correction factors for ambient air humidity, inlet air temperature and variation in ambient pressure were

measured to correct the final reading. Conversion of the differential pressure was accomplished by conversion tables and graphs provided by the manufacturer.

A schematic of the apparatus is as shown below.

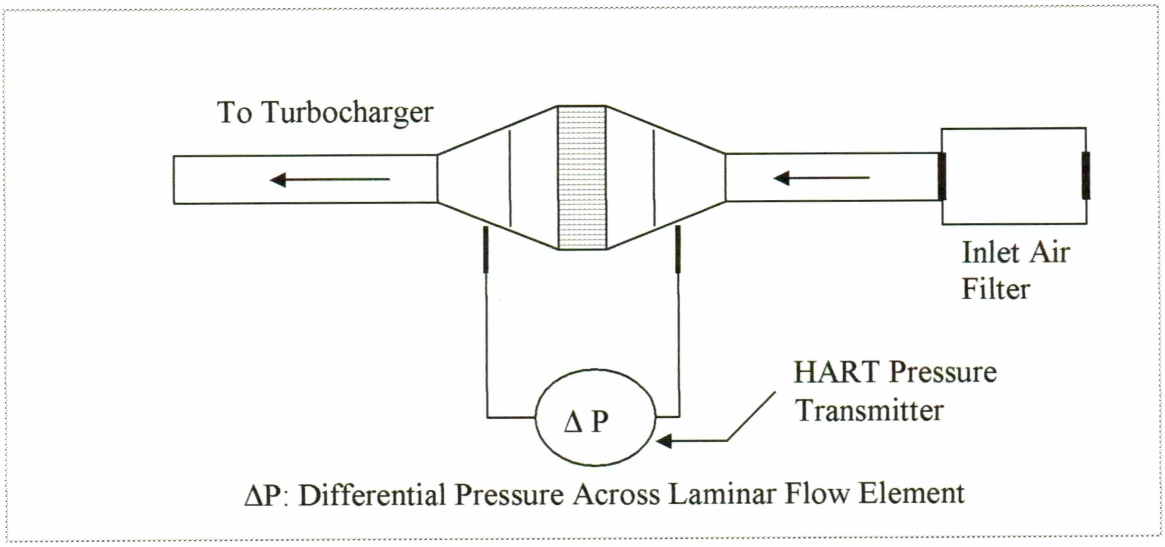

Figure 3.12: Schematic of Laminar Flow Element Set-Up

Throughout testing, periodic checks were made to ensure that the capillaries of the laminar flow element were never clogged with dirt or dust. The differential pressure meter was directly coupled to the main DAQ for continuous monitoring and logging of air data during testing.

3.7 Fuel Flow Measurement

Two different methods were used to measure the fuel flow rate to the generator. The first utilized a load cell located at the base of the particular day tank used during an individual test and the second used information available through the engine CAN bus data.

Method 1: Load Cell

Load cells are constructed with strain gauges assembled in a Wheatstone bridge, with the active gauges installed on the beams that are deflected by load. When the beam is deflected by the load, the resistivity of the strain gauge changes in proportion to the load applied, resulting in a change in the voltage output from the bridge circuit. Load cells, therefore, should provide a simple and accurate method for measuring the fuel flow rate to the diesel engine. The change in the weight of the tank is measured by the load cell and may be directly translated to the fuel consumed over a period of time. Most load cells have a temperature compensation to eradicate any inaccuracies caused due to change in ambient temperature.

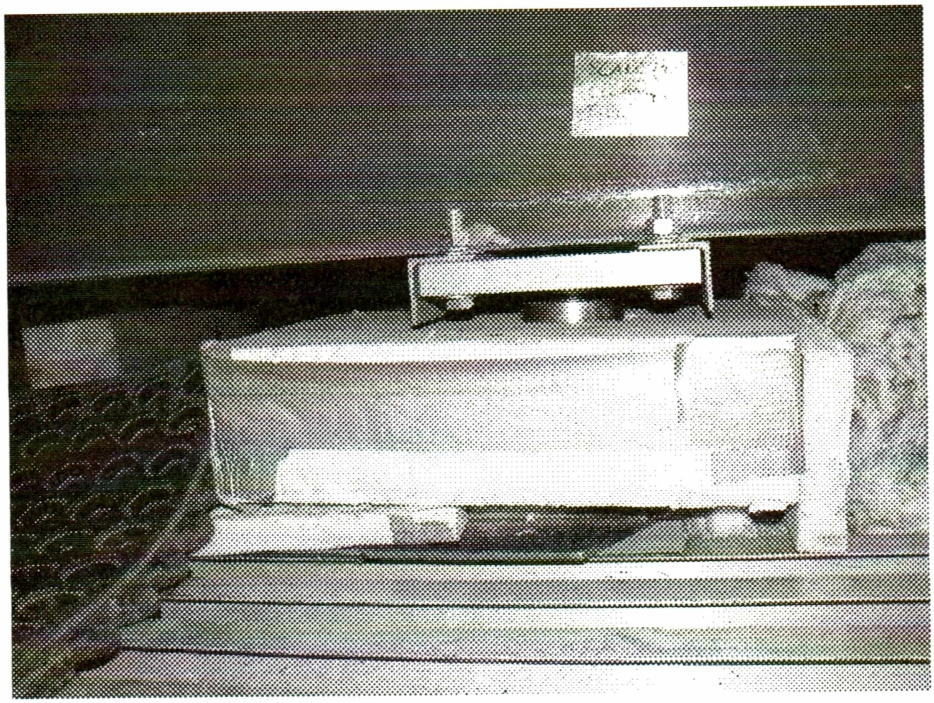

Figure 3.13: Load Cell

The method calls for placing a single load cell at one edge of the day tank, while the other end was fixed and supported by a metal plate. For this purpose, an Omega Tank Weighing Assembly load cell was used. The tank weighing assembly provides a flat

rectangular plate, which is mounted on the load cell, to effectively position the day tank. The mounting surface is self adjusting to up to 2° and has a thermal expansion correction up to +/- 1/6". During placement of the load cell, it was ensured that the day tank remained completely horizontal, using a level meter. The placement of the load cell was such that exactly half the combined total weight of the tank and the fuel was supported by the load cell.

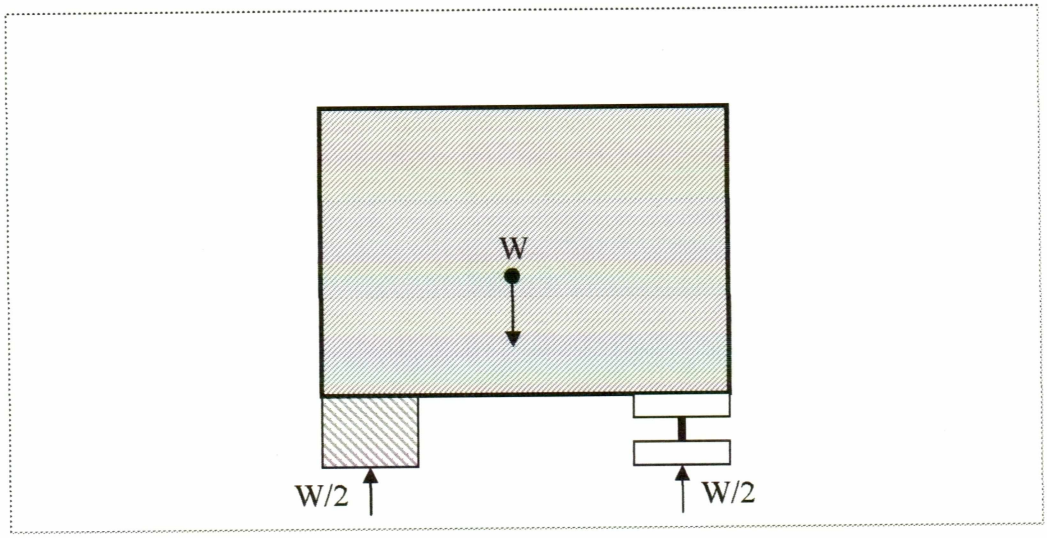

Figure 3.14: Schematic of Load Cell Set-Up

The load cell was calibrated by adding a fixed known quantity of the test fuel and measuring the load cell response. During calibration, precautions were taken to maintain the load cell at a constant temperature.

During operation of the test bed, the load cell response was seen to be affected by the following parameters.

1. The load cell was placed directly on the conex floor. During engine operation, the vibrations produced by the engine seemed to affect the load cell response, with a small amount of distortion evident in the load cell output. To minimize this

distortion, the entire day tank was placed on a rubber sheet, to help absorb some of the engine vibrations.

2. A second parameter, and probably a more important one, was the effect of ambient temperature on the load cell response. During continuous generator operation, the average change in the ambient temperature inside the conex was approximately 20 °C. This variation in temperature did cause a small drift in the load cell output. To rectify this fault, the load cell was maintained at a temperature of 100° F, using heating tape. This ensured that the load cell remained at a constant temperature during all experimentation.

Even after employing preventive measures to remove any error in the load cell output, there was some residual drift in the overall fuel reading. In order to verify the load cell output, fuel flow data, available from the engine CAN bus information, was used.

Method 2: CAN Bus Data

The second source for fuel flow measurement was the instantaneous fuel flow data available from the engine CAN bus. The CAN bus is an information transmission protocol available on the DDEC Series 50 engine.

The CAN bus information was accessed via a data port in the engine control panel and converted into useful information using the LabVIEW interface. Data acquired at ten second intervals incorporated the instantaneous fuel flow rate in liters per minute. The CAN bus fuel data was decoded using the LabVIEW software and converted to a readable format but the data was not modified in any way.

During all fuel flow rate calculation, fuel flow rates from both the available data sets were analyzed. It was verified that there was not a large error or difference between the

two readings. Throughout the testing period, both data sets were found to be very similar. However the CAN Bus data proved to be more useful as the data were considerably less noisy.

In order to verify the fuel consumption data from the engine CAN bus, the data were compared with the logged fuel transfers from the bulk fuel storage tank. It was seen that the total fuel consumed, as indicated by the engine CAN bus data and by the fuel removed from the bulk fuel storage tank, differed only by 4.7%, which falls within the accuracy range of the CAN bus fuel flow information, which is +/- 5%.

4.0 TEST FUELS

4.1 Primary Test Fuels

The Syntroleum S-2 and Syntroleum arctic grade, S-1, were the primary test fuels for the entire experiment. The S-2 may be characterized as the premium blend from Syntroleum (with properties similar to conventional No.2 diesel), as compared to S-1, which is predominantly meant for colder arctic temperatures and may be comparable to conventional No.1 diesel. Tests were conducted on pure streams of S2 and S1 fuels along with a blend of S2: conventional diesel in a 50:50 ratio.

4.2 Base Fuel

The base fuel used during testing was conventional No.1 Diesel fuel, commercially used in diesel engines and purchased locally in Fairbanks. During winter, as temperatures fall well below -30° C, conventional No.1 diesel is commonly sold by all vendors. The primary purpose of the base fuel was to provide a comparative emissions performance between the S1 and S2 synthetic diesels and conventional diesel. All flow and emissions measurements made for the S-1, S-2 and the base fuel were similar in all aspects.

5.0 TEST CYCLES

Two test cycles were outlined prior to testing. These test cycles were applied to the generator throughout testing. The following is a brief description of the outlined cycles.

5.1 Variable Load Profile

In order to facilitate engine break-in and simulate a real-time load on the generator, the test-bed was operated on a variable load profile, for most part of testing. The load profile varied from 60 KW to 120 KW, with increments of 5 KW in an approximate sinusoidal fashion. The time period for the cycle was one hour.

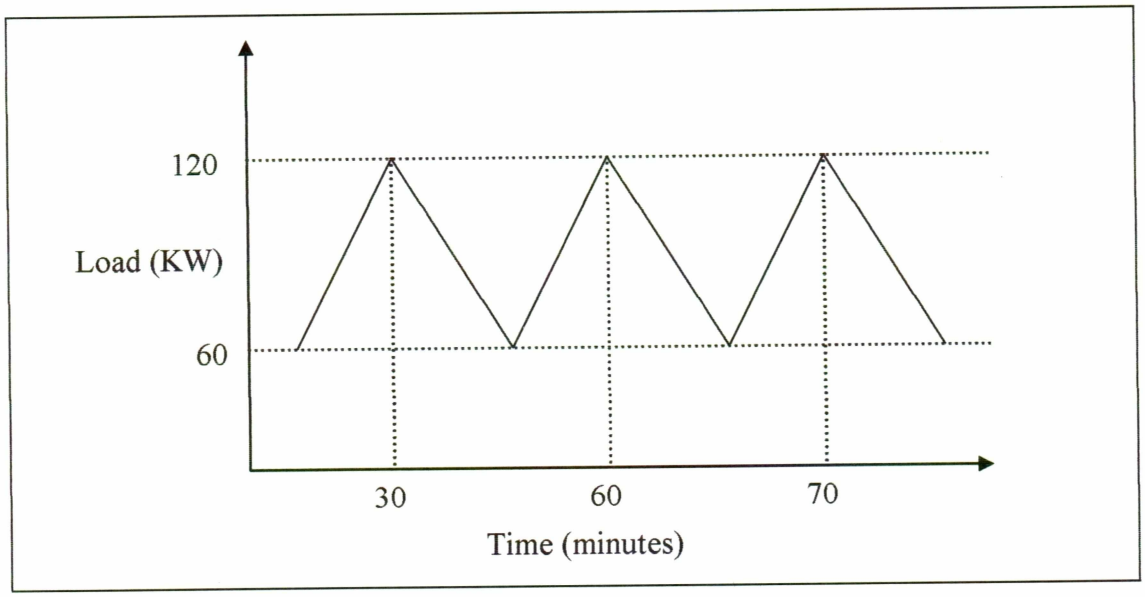

Fig 5.1: Variable Load Profile

5.2 5 Mode Test Cycle

The 5 mode cycle is described in the CFR, Chapter 40 Part 89. The cycle is specified for testing emissions from non-road constant speed compression ignition engines. The cycle dictates 5 steady state operating conditions at which the generator will be operated for a minimum period of five minutes at each loading condition. It also provides weighting factors for the five modes to arrive at the final emissions values. The five mode cycle as depicted in the code of federal regulations is show below.

Table 5.1: EPA 5 Mode Test Cycle

Mode Number	Engine Speed	Observed Torque (Percentage of Max. observed)	Minimum Time in Mode (minutes)	Weighting Factors
1	Rated	100	5	0.05
2	Rated	75	5	0.25
3	Rated	50	5	0.30
4	Rated	25	5	0.30
5	Rated	10	5	0.10

6.0 TEST PROCEDURE

Testing was conducted in four phases: 1) Break-in on conventional fuel, 2) a 1530 hour test on clean synthetic S2 fuel, 3) a 710 hour test on clean synthetic S1 fuel, and 4) an emissions testing phase where tests were conducted on both conventional and clean fuels while adjusting load and injection timing

Phase I: Engine "Break In"

The Series 50 diesel generator was purchased directly from Detroit Diesel. Prior to its installation at the UAF Energy Center, the generator was fitted, at Detroit Diesel Anchorage, with an external after-cooler and an external radiator. Regarding the "break-in" time for new engine, it was understood from the local DDEC representative that most of the Series 50 diesel engines are still settling in at 5000 hours, but most of the engine wear associated with the engine break-in occurs in the first 250 hours. With this in mind, a realistic "break-in" period of 250 hours was decided. During this period, the engine was operated on conventional diesel, procured from a local vendor. The generator was operated on the variable load profile, with the load varying from 60 KW to 120 KW, with a time period of one hour.

The engine "break-in" period provided an opportunity to assess installed instrumentation and equipment. Data pertaining to engine emissions and other necessary parameters were logged at periodic intervals. All information collected included a time stamp, indicating the date and time of the entry using the National Instruments LabVIEW software and hardware. The data were then analyzed to ascertain normal running conditions of the generator and installed instrumentation.

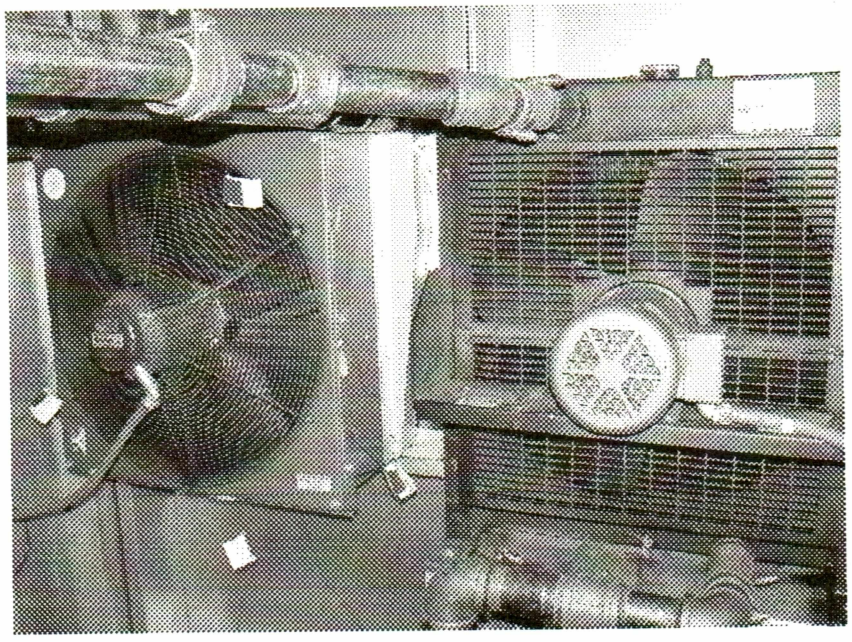

Figure 6.1: External Radiator and After-Cooler

After completion of the initial break in period, the response from all installed sensors and critical equipment were checked and re-calibrated if required. Calibration procedures followed were either provided by the manufacturer or the best available method was used. Calibration of the DAQ was assisted using a Fluke process calibrator, allowing National Institute of Standards and Testing (NIST) traceability of the signal read-out devices. As tests progressed additional refinement of the DAQ was done as appropriate.

Phase II

In order to attain the primary objective of testing and to meet project deadlines, the generator was operated on the S-2 fuel, immediately after completing the mandatory 250 hours on conventional diesel. Initial data (excluding emissions) pertaining to engine thermal efficiency was logged and periodically analyzed. The generator was monitored for any system drift or performance deterioration. Data collected did not suggest any major difference in performance between the conventional and the S-2 fuel. The only noticeable difference was a minor increase in fuel consumption on the S-2 fuel, which

was then attributed to the lower heating value and density of the S-2 fuel oil. With no noticeable abnormalities in the engine performance, the generator was operated on the S-2 fuel for the next 1530 hours of testing, during which a total of 10,490 gallons of S-2 fuel was consumed at an average of 6.85 gallons/hour. During the entire 1530 hours of testing, the generator was predominantly operated on the variable load profile.

Phase III

Testing on the S-1 fuel commenced in October, 2004, which is the beginning of winter in Fairbanks Alaska. The generator was operated on the variable load cycle. Similar to the S-2 fuel, no abnormalities were seen during operation. The generator was operated on the S-1 fuel for the next 710 hours, where a total of 4,530 gallons of fuel was consumed at an average of 6.38 gallons/hour. A similar 300 gallons of S-1 fuel was maintained in the second day tank, for emissions testing.

Phase IV

At the conclusion of the 2000 hour test, there was sufficient fuel reserved for emissions testing. Fuel storage and supply was maintained with the two day tanks located inside the conex, as the bulk fuel storage tank was moved to the Fairbanks North Star Borough bus station for a subsequent project. Difficulties with the emissions equipment (discussed below) and extended discussions with Detroit Diesel over software IP issues prevented the completion of the injection timing experiments during the 2000 hour test.

In the initial test plan all emissions tests were to be conducted during the three phases of testing. Initial baseline testing was to be conducted on conventional diesel and then on the synthetic fuels. All emissions tests were to be completed prior to the mandatory 2000 hours of operation on the synthetic fuel.

In order to record continuous emissions, a NOVA model 7466K portable engine exhaust analyzer was purchased. The analyzer used a Non Dispersive Infra Red (NDIR) detector to measure CO, CO_2, and HC and electro-chemical detectors for NO and NO_2. The sample probe has a tri-filter element to remove any particulates, while the analyzer had a secondary filter and a drain pump to remove any moisture in the sample exhaust. Calibration gases for the analyzer were purchased from Scott Gas. The calibration gases used were BAR 97 with a nominal accuracy of +/- 1%. During initial calibration, the analyzer output was found to be accurate and repeatable. At this juncture, the DAQ installation was incomplete and hence continuous emissions monitoring could not be conducted. In order to document baseline emissions on conventional diesel, a set of spot emissions tests were conducted at the end of Phase I testing. The analyzer was operated for no more than 1 hour and emissions readings were taken at 5 different engine loads during which the analyzer showed poor repeatability. During re-calibration of the analyzer, a continuous drift in the CO emissions signal was observed. Upon recommendations from the manufacturer the analyzer was sent back for inspection. The drift in the CO emissions was found to be due to the corrosion of the electro-chemical sensor resulting from the sulfur emissions from conventional diesel. The turnaround time for installing the electro-chemical sensor was two weeks, during which engine operation continued and the experiment stepped into Phase II of testing.

With a new electro-chemical sensor and the DAQ in place, two runs of continuous emissions monitoring were conducted on the S-2 synthetic fuel with each run lasting for 2½ hours. On comparing emissions from the two runs, the analyzer showed very poor repeatability and it was noticed that the analyzer reading did not return to zero even when operating in ambient conditions, indicating that there was some amount of residual emissions still present in the analyzer. A quick calibration check indicated that the analyzer calibration had drifted. Discussion with the manufacturer revealed that the portable analyzer was not meant for continuous emissions monitoring and was reliable and accurate only when used for spot emissions tests. If a portable analyzer were to be

used for continuous emissions monitoring, it should be operated for no more than 10 to 15 minutes at a given time on the sample exhaust, and a period of 5 to 10 minutes should be allowed for the analyzer to purge itself and remove any residual emissions, allowing the analyzer read-out to return to zero emissions levels.

A second obstacle posed by the NOVA analyzer was the resolution provided on the CO output. On average, CO emissions in typically well-tuned diesel engines range from 80 to 120 ppm. The range of the CO sensor on the NOVA analyzer was 0 to 10 %, with a resolution of 0.01%, which is a 100 ppm. With the analyzer operating at the very low end of its range and with the given resolution, it did not provide the required accuracy for CO measurements.

Although there were problems with the NOVA emissions analyzer, testing continued. Test phases I and II were almost completed, when it was decided to rent a second analyzer for emissions monitoring. At the end of Phase II and Phase III of testing 300 gallons of S1 and S2 fuel were stored in the two day tanks for emissions testing. Emissions testing proceeded as soon as the mandatory 2000 hours of testing on synthetic diesel was completed. Emissions equipment was rented from Clean Air Rentals, located in California. They were highly recommended based on the quality of their emissions equipment. With NDIR sensors being highly affected by any amount of moisture in the sample exhaust, an ECOM emissions analyzer was rented which used electro-chemical sensors for detecting all non-hydrocarbon emissions which included CO, CO_2, NO, NO_2 and O_2. The ECOM analyzer used proprietary ECOM data acquisition software to gather and store information from the analyzer. A separate JUM FID analyzer was rented for measuring HC emissions. The FID analyzer was calibrated on propane calibration gas and hence all THC results are hence based on propane equivalent. The FID analyzer utilized the available DAQ system for storing all data output from the analyzer.

Both analyzers, the ECOM and the FID, were rack mounted inside the conex. Sufficient space was provided around the analyzer for easy access to fittings and gas connections (in the case of the FID analyzer). Sample exhaust supply to both analyzers was through a single ¼" heated sample line. The sample line was maintained at a temperature of 250°F to prevent the condensation of any water. The flow after the sample line was split into two directions. Flow direction 1 provided sample exhaust supply, to the FID analyzer. Flow direction 2 was directed to a condenser. This ensured that the gas sample to the ECOM analyzer was rid of any moisture, and hence the analyzer was able to maintain repeatability in readings. The condenser outlet temperature was maintained at 5°C. Two thermocouples placed in-line with either direction of flow continuously monitored flow temperatures to the analyzers.

Prior to the heated sample lines, a heated filter and a heated probe assembly were used to extract the flue gas from the stack. The heated probe was suspended inline with the exhaust gas, through 2 ½" holes drilled into the exhaust stack. The probe was placed well inside the stack, and installed to ensure that it did not draw ambient air during testing. The probe led to a heated particulate filter. The filter and the probe were maintained at a temperature of 250 °F.

The measurement of PM in exhaust is a cumbersome exercise, in which a constant velocity tunnel is created wherein a filter is exposed to the exhaust gas. The difference in the weight of the filter before and after the test period is a representation of the PM in the exhaust gas. These gravimetric tests need to be conducted with extreme caution since a small amount of contaminant on the filters could give misleading results. In order to get good information about the PM produced by the test fuel, it was decided that an opacity meter would be used to estimate exhaust opacity, which would then be converted into a PM reading in grams/KW-h.

An Environmental Monitor Service opacity meter Model 750 was installed in the exhaust stack. The opacity meter would provide opacity readings for different loading conditions, which would be correlated to PM emissions. The opacity meter consists of a control unit, a transmitter (light source) and a detector. The transmitter and the detector were installed on the exhaust stack and were mounted on a 1 ¼" flange. In order to maintain the lenses of the transmitter and the receiver free from soot particles a dedicated purge air supply was plumbed in. The control unit was mounted inside the conex, and the output, a 4 to 20 mA signal, was incorporated into the DAQ.

Even with a clean path, with the engine not operating, initial readings obtained from the opacity meter suggested that there was a certain amount of residual opacity in the line. This was thought to be either a problem with the misalignment of the two lenses, or the opacity meter was being affected by ambient light. Both lenses were then removed and assembled indoors in the laboratory. It was noticed that the ambient light did not have any affect on the opacity reading. The transmitter is a flickering light source and hence is not affected by ambient light. In order to understand the effect of lens alignment on the meter, a laboratory test bench was prepared for the meter. The test bench helped mount the lenses with minimum or no misalignment. Even with the lenses perfectly aligned some residual opacity did exist. Upon manufacturer recommendations the opacity meter was sent back for inspection. It was found that the erroneous reading was due to a faulty electronic component in the control unit.

With the faulty electronic component replaced the opacity meter was re-installed on the exhaust stack and the purge air lines plumbed in. However, the opacity readings did not seem to improve. Residual opacity readings got worse, with the opacity meter showing a residual opacity of 44%. Calibration and adjustment tools provided on the control unit were not of any assistance. With such a high residual error, it would not have been possible to accurately predict the PM emissions in grams/KW-h. We are therefore unable to report the exhaust opacity values during this study.

All the gaseous emissions data were obtained by operating the generator on a 5 Mode test cycle as described in the CFR Title 40, which requires that each mode be run for a minimum time period of 5 minutes. Prior to each emission run and after each run, a calibration check was conducted on both emissions analyzers, with the laboratory calibration gas. If the analyzer reading was not within 1 % of the full scale reading the data were discarded and the analyzer was re-calibrated. This ensured accuracy of the recorded emissions data. Each emissions run was conducted with similar parameters. No change in equipment or set-up was made during testing.

Emissions measurements were conducted for all regulated gaseous emissions. At no point during experimentation was particulate analysis conducted. Emissions data gathered on the synthetic diesels and conventional diesel utilized the same apparatus. When operating on conventional diesel extra care was taken to remove any moisture in the sample line. Experience with the NOVA portable analyzer indicated that emissions analyzers are prone to damage caused by sulfur that deposits on the sensors, during the course of testing. In addition to using a single set of calibration gases to check the emissions measurements during the course of testing, a "standard state" set of measurements was taken at the beginning and end of testing to assure that no changes had taken place in the engine during the tests, and that changes in emissions were due to fuels and not due to the wear or other changes in engine performance. These "standard state" measurements indicated no significant changes in engine performance or deterioration of emissions equipment, and therefore any change in observations could be attributed to the changes in fuel or injection timing.

Emissions were recorded at five different generator load levels. i.e. 100 %, 75 %, 50 %, 25% and 10%, which translate into 125 KW, 94 KW, 62 KW, 31 KW and 15 KW, respectively. In order to evaluate any change in combustion characteristics of the synthetic fuel as compared to conventional diesel, emissions testing was also performed at three different injection timings, along with the set factory injection timing of 10

degrees before TDC. Henceforth, the factory set injection timing will be referred to as injection at "zero" degrees. The injection timings chosen, with respect to the zero degree injection, were a 3 and 5 degrees injection advance and a 3 degree injection retard. Emissions and flow data, including but not limited to air and fuel mass flow rates, were measured at all injection timings, to achieve a better understanding of the fuel/engine performance under different operating conditions.

7.0 EMISSIONS RESULTS

The following four tables list the emissions and the brake specific fuel consumption from tested fuels at 0 degrees, 3 and 5 degrees advance, and 3 degree retard.

Table 7.1: Emissions at Zero Degrees Injection Timing

	CO	NOx	HC	BSFC
Test Fuel	(g/KW-h)	(g/KW-h)	(g/KW-h)	(KW-h/gal)
Base Fuel	2.657	18.32	0.334	14.64
S-2	1.911	16.08	0.271	14.61
S-1	1.612	16.97	0.21	14.15
Blend	2.35	17.75	0.273	14.48

Table 7.2: Emissions at 3Degree Injection Timing Advance

	CO	NOx	HC	BSFC
Test Fuel	(g/KW-h)	(g/KW-h)	(g/KW-h)	(KW-h/gal)
Base Fuel	2.451	22.23	0.256	14.95
S-2	1.604	19.68	0.174	14.61
S-1	1.748	21.56	0.246	14.07
Blend	2.302	22.11	0.234	14.95

Table 7.3: Emissions at 5 Degrees Injection Timing Advance

	CO	NOx	HC	BSFC
Test Fuel	(g/KW-h)	(g/KW-h)	(g/KW-h)	(KW-h/gal)
Base Fuel	2.485	23.44	0.386	15.01
S-2	1.743	20.98	0.235	14.85
S-1	1.955	25.19	0.225	14.09
Blend	2.295	23.85	0.326	14.91

Table 7.4: Emissions at 3 Degrees Injection Timing Retard

	CO	NOx	HC	BSFC
Test Fuel	(g/KW-h)	(g/KW-h)	(g/KW-h)	(KW-h/gal)
Base Fuel	3.11	13.80	0.420	15.01
S-2	2.007	11.72	0.215	14.04
S-1	2.093	11.05	0.268	13.52
Blend	2.183	12.95	0.224	14.16

8.0 DISCUSSION OF RESULTS

Within the boundaries of experimentation, it is evident that the synthetic fuel performed noticeably better than conventional diesel with respect to regulated emissions. On the basis of emissions produced, the synthetic diesel responded with lower emissions per kilowatt-hour of energy produced. When comparing energy consumed, the synthetic fuel had a lower mass flow rate in lb/KW-h as compared to No.1 diesel. It should also be noted that these improvements could be greatly amplified with the use of catalytic clean-up systems.

As mentioned earlier emissions testing was performed after the mandatory 2000 hours of operation on the synthetic fuel was completed. During emissions testing it was observed that all the test fuels showed higher CO emissions, than what would generally be expected on a Series 50 diesel engine.

The following table lists CO emissions for a typical Series 50 diesel engine, operating on No.2 diesel, as compared to the CO emissions obtained on the test bed when operating on conventional (No.1) diesel.

Table 8.1: Typical Emissions from a DDEC Series 50

% Loading	100	75	50	25
Typical Series 50 (grams/hour)	40	37	36	51
Test Bed (grams/hour)	561	208	78	73

As seen from the above table, CO emissions are much higher for the test bed as compared to typical CO emissions from a Series 50, especially at higher loads. All external parameters that may contribute to the higher emissions, such as a restriction in the air

inlet line and line pressure drops were checked and found to be within the normal operating range.

As mentioned in the literature review, synthetic diesels may tend to have a lower lubricity value as compared to conventional diesels. It was thought that initial operation on the synthetic fuel with low lubricity may have damaged the sensitive fuel injectors of the Series 50. After completing all emissions testing, all four injectors were replaced with new ones. However, even with new injectors in place, CO emissions did not improve.

Several probable explanations for the high CO emissions were investigated, reduced air flow being recognized as being one major possibility. In order to ascertain that there was no obstruction to the inlet air flow, an in-house experiment was conducted, in which the inlet air line, which included the laminar flow element and the air inlet filter, was disconnected. The engine was allowed to draw in ambient air from outside the conex. It was then seen that the CO emissions were reduced by 50%, decreasing from 500 ppm at full load to 250 ppm. The decrease in the emissions was attributed to the fact that, after a period of operation, the ambient air inside the conex is heated. The hot air is less dense and rises and settles at the conex ceiling where the engine air inlet is located. Therefore, during normal operation of the engine, the inlet air is less dense, which was seen to have an effect on the emissions. A second in-house experiment was conducted to find the association between the emissions and the cylinder inlet air temperature. With sub-zero ambient conditions, the after-cooler cooled the compressed air from the turbo-charger to approximately 5°C. During the experiment, the after-cooler was momentarily switched off and the compressed air temperature was allowed to rise to a maximum of 40°C. It was observed that when the after-cooler was disengaged the emissions increased drastically. At full load with the after-cooler not operating, CO emissions peaked at 650 ppm at 40°C compressed air temperature.

The final piece of the puzzle was provided by Mike Atchley, who is the sales representative for DDEC in Alaska. During a conversation with he stated that the higher CO emissions were a product of an improperly sized turbocharger. A DDEC Series 50 diesel engine is generally meant for a normal operating speed of 1800 rpm and not 1200 rpm. When the engine was procured from DDEC no modifications were made to the engine to effectively operate at 1200 rpm. Therefore, with the turbo operating at only half it's potential, it did not produce the required boost pressure for combustion. As a result, due to incomplete in-cylinder combustion, the CO emissions were seen to drastically increase. Due to this engine anomaly, all emissions results will be normalized with respect to conventional diesel.

A test protocol was followed through the testing. Although emissions from conventional diesel were used as a base for emissions comparison, the S1 fuel was maintained in order to check for any system or instrument drift during testing. In due course of testing, two system drift checks were made: a mid-point system check, where only half of the emissions tests were completed and an end-point check when all the emissions tests were completed.

8.1 Engine Emissions at Zero Injection Timing

8.1.1 CO Emissions

Both grades of synthetic fuels, the S-1 and the S-2, were seen to perform better and have lower regulated emissions as compared to conventional diesel. Tests conducted with no change in injection timing saw a decrease in the CO emissions of 39.88% on S1, 28% on S2 and 11.56% on the blended fuel. On the basis of the literature review, a high cetane number, should translate into lower CO emissions. However in advanced diesel engines equipped with the EGR technology, the cetane number has a lesser effect on CO emissions.

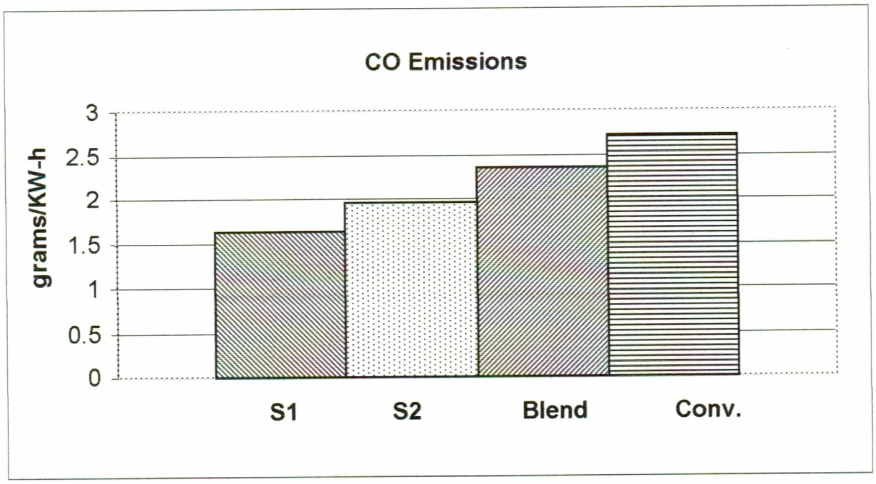

Figure 8.1: CO Emissions at Zero Injection Timing

Therefore at this juncture a reduction in CO emissions while operating on synthetic fuel can merely be stated, and due to experimental limitations cannot be investigated further.

8.1.2 NOx Emissions

Preliminary testing conducted by Syntroleum on the S2 fuel, had indicated an increase in NOx emissions by 4%, when the engine the engine was loaded with a dynamometer and operated on the FTP transient emissions cycle. During the current testing, NOx emissions were actually seen to decrease when the engine was operated on either synthetic fuel. A decrease of 8.69% was observed on the S1 fuel, while the S2 and the fuel blend showed a decrease of 12.17% and 3.1%, respectively.

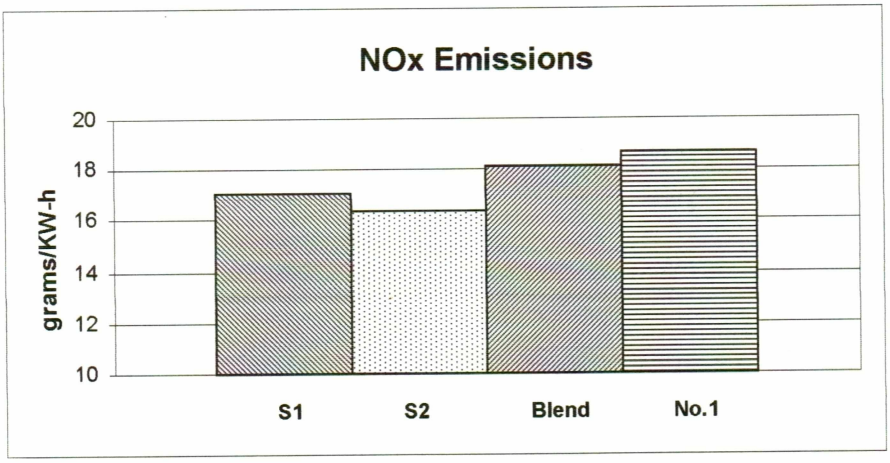

Figure 8.2: NOx Emissions at Zero Injection Timing

The results obtained from this work are consistent with most of the reviewed literature, which states of lower NOx emissions with decrease of fuel aromatic levels. However, it must be noted that in view of the final application of test results, the above emissions testing was conducted while operating on the EPA 5 Mode steady state test cycle and may differ from results obtained on the FTP transient emissions cycle.

8.1.3 HC Emissions

All HC emissions were calculated as propane equivalent. HC emissions on synthetic fuel were much lower as compared to conventional diesel. A decrease of 37.65%, 18.82% and 18.23% were seen on the S1, S2 and blended fuel, respectively.

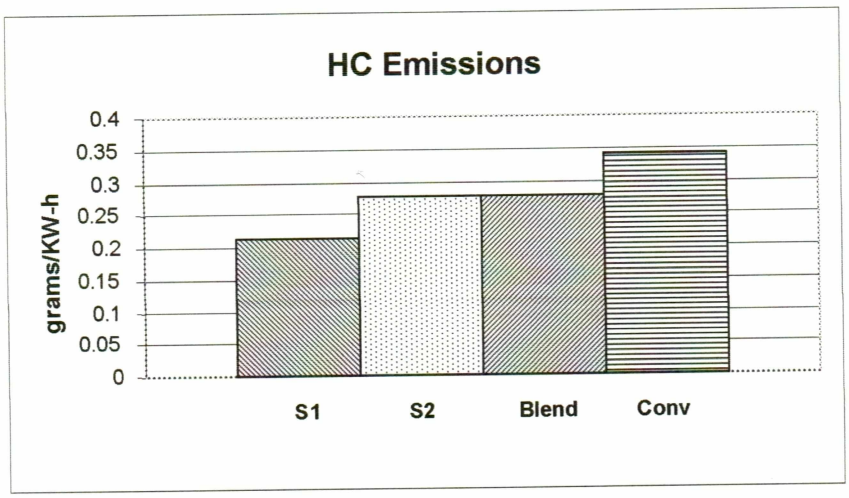

Figure 8.3: HC Emissions at Zero Injection Timing

8.1.4 BSFC

A very essential measurement during testing, BSFC, is an excellent indication of engine efficiency for a particular fuel. From the perspective of heating values, on an average, both synthetic fuels had 10 % lower heating value as compared to conventional diesel. This however translated into a 6 % decrease in fuel consumption at full load for the S1 fuel and a 10% decrease in fuel consumption for the S2 as compared to conventional diesel. The following graph depicts the specific fuel consumption for the fuels tested.

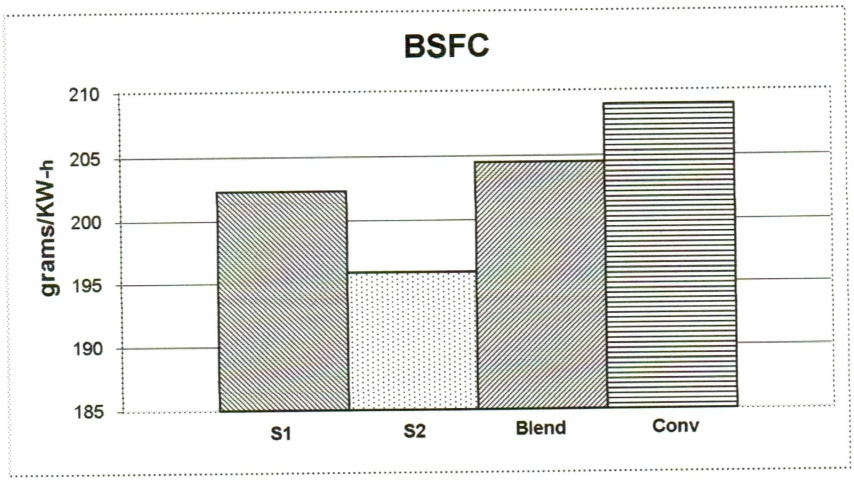

Figure 8.4: BSFC at Zero Injection Timing

As seen from the graph the fuel consumption decreases when operating on the S1 fuel oil. Operation on S2 shows a very minor decrease in fuel consumption. The decrease in BSFC was concurrent to similar F-T fuels tested by other agencies [26].

Due to proprietary reasons, analysis of either synthetic diesel was prohibited at any time during emissions testing. Hence, the decrease in the regulated emissions could not be attributed to a particular fuel oil component.

8.2 Engine Emissions at Different Injection Timings

As mentioned in the test procedure, emissions tests were conducted at three different injection timings, other than the factory setting. The primary objective of the injection timing (IT) change was to document the behavior of the test fuel under different operating conditions. The IT change was conducted with the help of proprietary software made available by Detroit Diesel. The three chosen injection timings were three and five degrees injection advance and a three degree injection retard. All three fuels and the fuel blend were tested at the said injection timings and their emissions measured.

8.2.1 S1 Emissions with Change in Injection Timing

As seen from the graph, CO emissions were at a minimum, when the engine was operated at the factory set injection timing as compared to the other three injection timings. CO emissions are seen to gradually increase with an injection timing advance, but a rapid increase is seen with an injection timing retard. Emissions increased by 8.4% and 22.7% respectively with a three and five degree injection timing advance, while an increase of 31.4% was seen with three degree retard in injection timing.

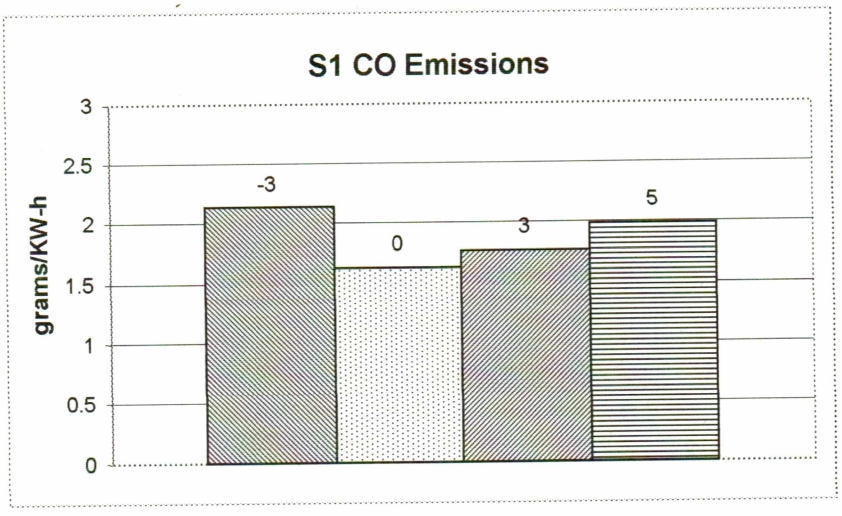

Figure 8.5: S1 CO Emissions at Different Injection Timings

NO emissions for the S1 fuel at varying injection timing followed a predictable path. With an advance in injection timing NO emissions increased. This may be explained by the fact that NO emissions depend upon flame temperatures and the time allotted to combustion. With an advance in injection timing, higher flame temperatures and more time for combustion translated into higher NO emissions. As seen the NO emissions were seen to increase by 27% and 50% respectively with a three and five degree injection timing advance, while a decrease of 34% was seen with a three degree retard in injection timing.

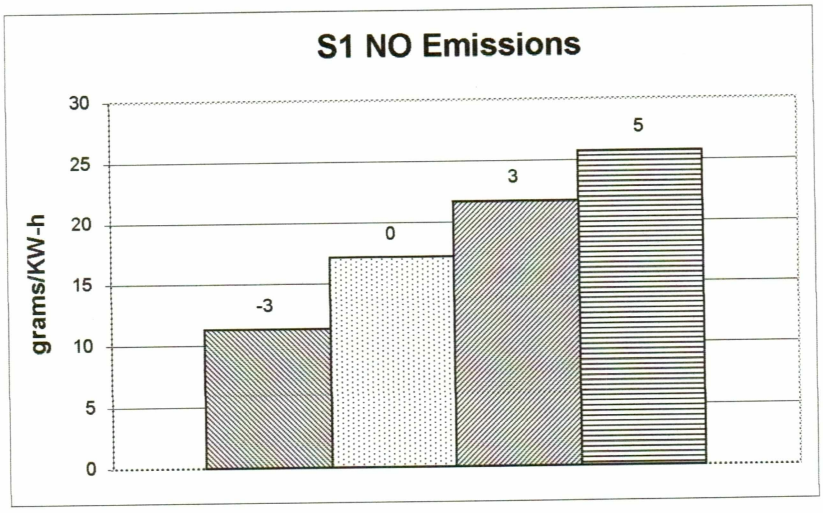

Figure 8.6: S1 NOx Emissions at Different Injection Timings

The HC emissions were seen to be lowest at the factory set injection timing. An increase in HC emissions was seen with an advance or retard of three degrees. HC emissions were seen to increase by 16.9% and 28.3% with a three degree advance or retard, with an increase of 8% seen with a five degree injection timing advance.

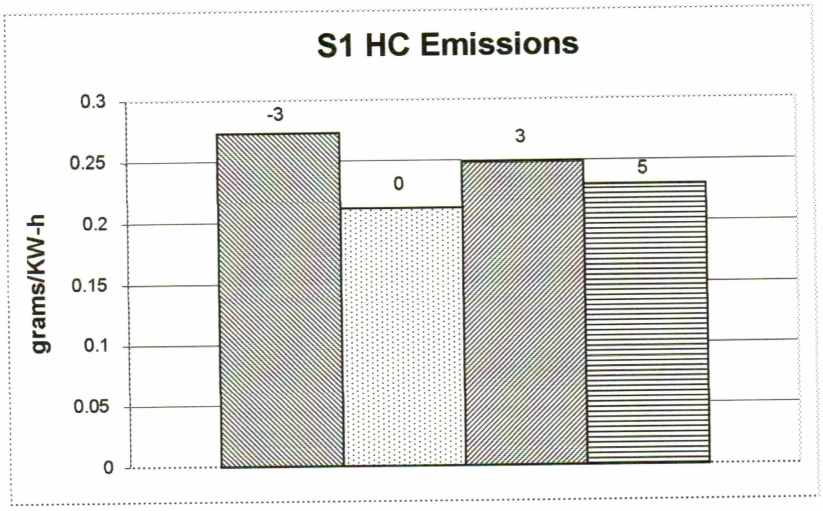

Figure 8.7: S1 HC Emissions at Different Injection Timings

8.2.2 S2 Emissions with change in Injection Timing

CO emissions for the S2 fuel decreased by 16.02% and 9.5% respectively, with a three and five degree advance in injection timing, while CO emissions were seen to increase by 5.08% with a three degree retard in injection timing.

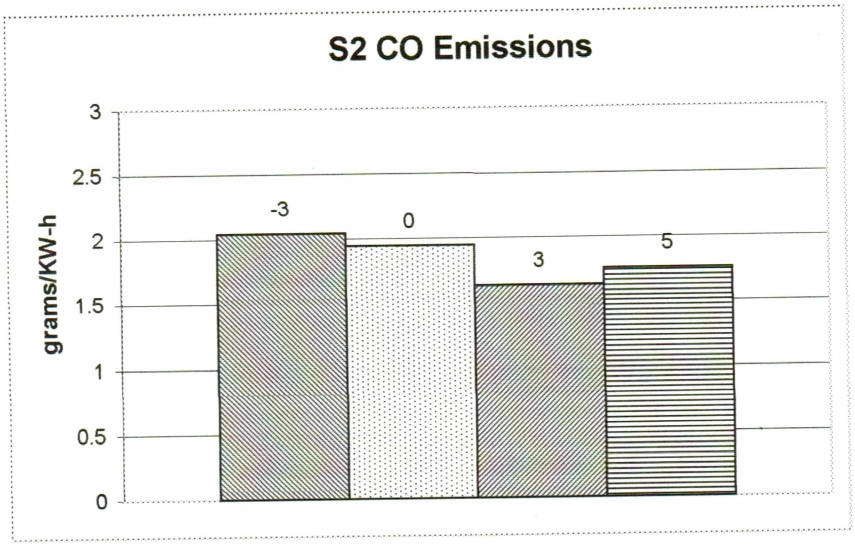

Figure 8.8: S2 CO Emissions at Different Injection Timings

NOx emissions on the S2 fuel followed a similar predictable path, with an increase of 22.36% and 29.47% respectively, with a three and five degree injection timing advance, while a decrease of 27.11% was seen with a three degree retard in injection timing.

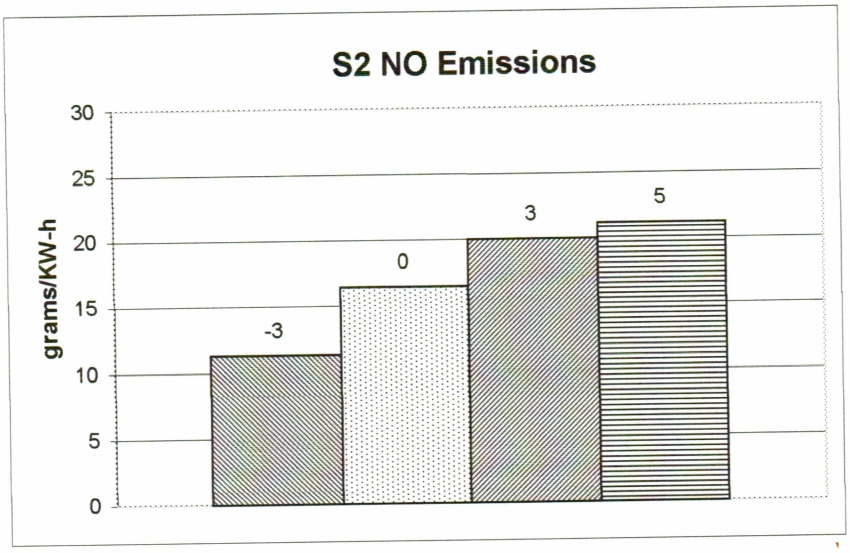

Figure 8.9: S2 NOx Emissions at Different Injection Timings

HC emissions were seen to decrease by 35.8% and 20.6% with a 3 degree advance or retard in injection timing, while a decrease of 13.7% was seen with a 5 degree advance in injection timing.

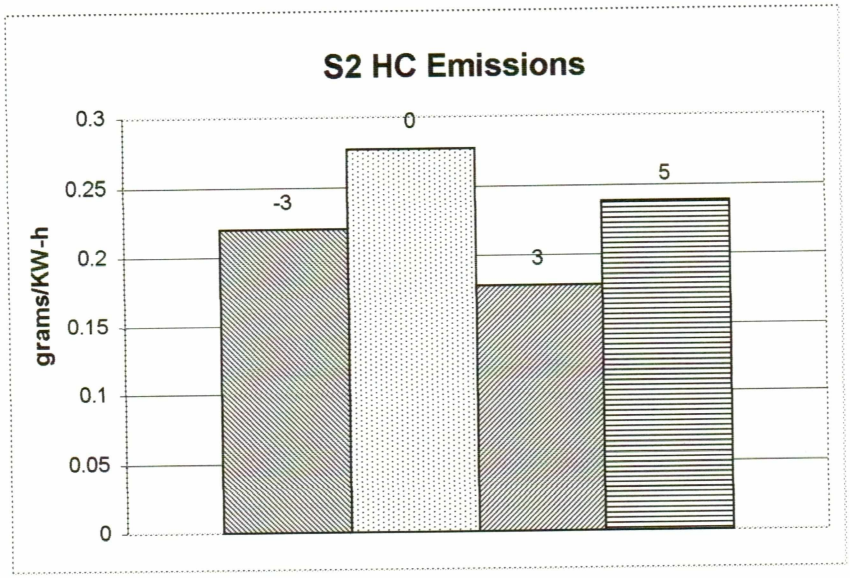

Figure 8.10: S2 HC Emissions at Different Injection Timings

9.0 PROBLEMS ENCOUNTERED DURING EXPERIMENTATION

All experimental work is generally accompanied by its share of problems. Measures are always taken to minimize error. Investigators invest a good portion of their time in identifying abnormalities and detecting causes of deviant behavior in the system. Following is a brief summary of the problems faced during this experimental analysis. Almost all problem sources were identified and rectified, although some abnormalities in the emissions could not be rectified as it was attributed to system design and could not be rectified in the given time frame of experimentation.

During the summer of 2004, there were a number of wildfires in the state of Alaska. Although the city of Fairbanks was safe from the fire, there were a weeks when the air quality was very poor due to thick smoke which blanketed the area. In order to maintain the project deadline, the generator was operational throughout the summer. The smoke particulates affected the three systems of the diesel generator, the after cooler, the radiator and the inlet air filter.

The conex is an enclosed space with no forced draught system in place for ventilation. As a result, ambient temperatures inside the conex were considerably higher than outdoor ambient temperatures. This implied that the after-cooler and the radiator would be operating on a continuous basis in order to maintain engine and inlet air temperatures. After a few weeks of operation, the coolant flow rate was observed to be higher than that seen during previous operation. This was attributed to a sticky scum that formed on the external surfaces of the radiator and the after-cooler due to the particulate filled air. Upon removal of the scum, the coolant and inlet air temperatures were seen to revert back to normal.

Since the air intake for the generator is located inside the conex, during normal operation, the generator draws air, for combustion, from inside the conex and not directly from the

outdoor air. During the end of summer, it was noticed that the inlet air filter had collapsed. With a collapsed filter, the laminar flow element, located downstream from the air filter, acted as a surrogate filter. Upon examination, it was observed that the air inlet filter was clogged and had to be replaced. Contaminated by dust and filter debris, the laminar flow element was sent to the manufacturer for cleaning and re-calibration.

After 962 hours of testing, a high pitched sound was noticed by one of the test engineers. Upon inspection it was found that a ball bearing on the turbocharger was damaged. The turbo-charger was replaced and testing was resumed. During the testing of any new fuel, it is imperative to understand the primary cause of failure and ascertain if the failure is fuel related. As the turbocharger uses the exhaust from the engine to produce compressed air, and has no contact with the fuel stream, we can safely assume that the turbocharger failure was not fuel related. The turbocharger failure may have been caused by the insufficient time allotted to engine idling during shut down after continuous operation at high loads. A short period of engine idle during shutdown allows the turbocharger to cool and reduce surface temperatures. With immediate shutdown without idling, the heat transfer rate from the turbocharger is low, therefore maintaining the turbocharger at a high temperature for a long period of time.

10.0 CONCLUSIONS

A long term durability test was performed on two synthetic fuels, the S-1 and S-2, manufactured by Syntroleum Corporation. The effects of the fuel on engine emissions and component wear, especially fuel injectors, were analyzed.

1. During the 2000 hours of continuous operation on the synthetic fuel, the engine performed well with no failures or breakdowns associated to the fuel oil. The highly sensitive fuel injectors of the Series 50 engine showed no signs of wear or deterioration. The long term durability test established that the synthetic fuel may be used as a substitute for conventional diesel, with no adverse effects on the engine.
2. With no aromatics, no sulfur and a very high cetane number, both synthetic fuels had lower gaseous emissions as compared to conventional No.1 diesel. CO, NOx and HC emissions were seen to decrease by 40%, 8.5% and 37%, respectively, on the S1 fuel and 28%, 12% and 18%, respectively, on the S2 fuel. Even with a lower heating value the BSFC was seen to decrease by 3% with the S1 fuel and 6% with the S2 fuel. A blend of synthetic S2 and No.1 diesel showed a decrease in emissions proportional to the quantity of S2 fuel.
3. Emissions testing performed at different injection timings indicated that the factory set injection timing was optimal for the S1 fuel. However, the S2 fuel displayed lower CO and HC emissions by 16% and 35%, respectively, along with a decrease in BSFC by 2%, with a 3° retard from the factory set injection timing, but the NOx emissions were seen to increase by 22%. Hence a 3° retard provided the best compromise between an increase in NOx emissions and a decrease in CO, HC and BSFC.
4. For the Series 50 engine, emissions performance at 1200 rpm differed considerably from that at 1800 rpm, with an increase in most regulated gaseous emissions.

5. Ambient conditions played a vital role in defining the performance of the diesel generator. Performance degraded with an increase in the ambient air particulates, with severe maintenance required on the radiator, after-cooler and the inlet air filter.

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APPENDIX A

Alaska Source Testing (AST) is a reputable emissions monitoring company located in Anchorage, Fairbanks. AST was hired by the UAF Energy Center to conduct PM emissions testing. Tests were conducted on the S1 synthetic fuel and No.1 diesel. Emissions measured in PPM are presented in units of lb/hr, lb/gal and grams/bhp-hr and are summarized below. Tests were conducted at the factory set injection timing.

	Load	Particulate Emissions		
Fuel	(KW)	lb/hr	lb/gal	g/bhp-hr
Synthetic S-1	125	0.094	0.01	0.246
	87.18	0.033	0.005	0.123
No.1 Diesel	125	0.12	0.013	0.313